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A Prospective Cohort Study of Adolescents' Memory Performance and Individual Brain Dose of Microwave Radiation from Wireless Communication

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Background: The potential impact of microwave radiofrequency electromagnetic fields (RF-EMF) emitted by wireless communication devices on neurocognitive functions of adolescents is controversial. In a previous analysis, we found changes in figural memory scores associated with a higher cumulative RF-EMF brain dose in adolescents.

Objective: We aimed to follow-up our previous results using a new study population, dose estimation, and approach to controlling for confounding from media usage itself.

Methods: RF-EMF brain dose for each participant was modeled. Multivariable linear regression models were fitted on verbal and figural memory score changes over 1 y and on estimated cumulative brain dose and RF-EMF related and unrelated media usage ($n = 669$–676). Because of the hemispheric lateralization of memory, we conducted a laterality analysis for phone call ear preference. To control for the confounding of media use behaviors, a stratified analysis for different media usage groups was also conducted.

Results: We found decreased figural memory scores in association with an interquartile range (IQR) increase in estimated cumulative RF-EMF brain dose scores: −0.22 (95% CI: −0.47, 0.03; IQR: 953 mJ/kg per day) in the whole sample, −0.39 (95% CI: −0.67, −0.10; IQR: 953 mJ/kg per day) in right-side users ($n = 532$), and −0.26 (95% CI: −0.42, −0.10; IQR: 341 mJ/kg per day) when recorded network operator data were used for RF-EMF dose estimation ($n = 274$). Media usage unrelated to RF-EMF did not show significant associations or consistent patterns, with the exception of consistent (nonsignificant) positive associations between data traffic duration and verbal memory.

Conclusions: Our findings for a cohort of Swiss adolescents require confirmation in other populations but suggest a potential adverse effect of RF-EMF brain dose on cognitive functions that involve brain regions mostly exposed during mobile phone use. https://doi.org/10.1289/EHP2427

Introduction

The rapid evolution of information and communication technologies (ICTs) during the past 20 y has caused an increase in man-made exposure to radiofrequency electromagnetic fields (RF-EMFs). However, the health effects of RF-EMFs are still unknown. Neurological functions are of special concern given that the brain is heavily exposed while calling with a mobile or cordless phone (Joseph et al. 2010). Present-day adolescents will likely have higher cumulative lifetime exposure to RF-EMF, and the developing brain might be particularly susceptible to RF-EMF–induced alterations up to 15 y of age (Kheifets et al. 2005; Luciana et al. 2005; Schüz 2005). In this age group, memory functions are particularly important because proper encoding, processing, and retrieval of information are required for learning. However, to date studies addressing this topic have produced inconsistent results.

Controlled-exposure studies in animals and humans have found limited evidence for both positive and negative effects of RF-EMF on memory performance and related neural processes (Bouji et al. 2012; Deshmukh et al. 2015; Hao et al. 2013; Jeong et al. 2015; Klose et al. 2014; Son et al. 2016). Among the few epidemio-logical studies, the Australian Mobile Radiofrequency Phone Exposed Users' Study (MoRPhEUS) cohort of 317 adolescents with a median age of 13 y observed faster but less accurate responses in working memory and associative learning tasks for frequent mobile phone users (Abramson et al. 2009). The same result was observed in relation to the number of text messages (SMS), which involve only marginal RF-EMF exposure. This may suggest that aspects other than RF-EMFs are the underlying cause of this association. A longitudinal analysis of the MoRPhEUS data indicated associations between mobile phone use and changes in response times for some cognitive tasks over a 1-y period, but the authors proposed regression to the mean as a potential explanation because associations were inconsistent and increase in exposure was mainly seen in those who had fewer calls and SMS at baseline (Thomas et al. 2010).

In the following Examination of Psychological Outcomes in Students using Radiofrequency dEvices (ExPOSURE) study by the same research group as MoRPhEUS, 617 primary school children were investigated and little evidence for cognitive effects due to RF-EMF was found (Redmayne et al. 2013). However, the number of calls was generally very low in these young children (8–11 y of age): a median of 2.5 and 2 calls per week for mobile phones and cordless phones, respectively, among those children using these devices.

In both studies, the RF-EMF exposure was assessed via self-reported number of calls, which usually yields an overestimation of the actual use by adolescents (Aydin et al. 2011). Further, personal exposure to RF-EMF is dependent on other factors such as the call duration, the distance of the device from the body (Joseph et al. 2010; Kühn and Kuster 2013), and the network used for calling. For instance, the global system for mobile communications standard (GSM) produces about 100–500 times higher exposure than the universal mobile telecommunication system (UMTS) (Gati et al. 2009; Persson et al. 2012). Furthermore, using mobile phone calls as a proxy for RF-EMF exposure ignores confounding by the media-related lifestyle impacting individuals' cognition, behavior, and emotion (Kuss et al. 2014; Kuss and Griffiths 2011, 2012; Roser et al. 2016). The present Health Effects Related to Mobile phone usE in adolescentS (HERMES) cohort was the first study in

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adolescents that used individually modeled RF-EMF doses and operator-recorded mobile phone use to investigate potential effects of RF-EMF exposure on cognitive functions (Roser et al. 2015). With this approach, cumulative RF-EMF brain dose was associated with a significant decrease in figural memory performance over a 1-y period (Schoeni et al. 2015), with a stronger decrease observed in right-side users.

The present study aims to follow-up our previous results using an approximate doubling of sample size. Further, we have updated the individual RF-EMF dose model using more recent information on adolescents' brain specific absorption rates (SARs) for different exposure scenarios and by calibrating self-reported call duration on objective operator-recorded call duration. In addition, the present study applies a new approach to control for confounding due to device usage in epidemiological RF-EMF studies.

Materials and Methods

Data of the prospective HERMES cohort study were collected in two independent sampling waves. The first wave of baseline investigations commenced in June 2012 among a cohort of seventh- through ninth-grade students from 24 secondary schools in Central Switzerland. A second wave commenced in April 2014 that included a new group of seventh- through ninth-grade students from 22 secondary schools. Of the 22 schools, 2 had already taken part in the first wave, 18 were newly recruited from Central Switzerland, and 2 were newly recruited from the Basel canton. Follow-up investigations were conducted approximately 1 y after each baseline until April 2016. Participating adolescents were recruited through an initial telephone contact by the head of the school and a subsequent informational visit in their respective classes by the study managers. Participation was voluntary and the informed consent of both adolescents and a parent was compulsory.

The data were collected during school lessons and consisted of completing a paper questionnaire to assess the adolescents' mobile phone and media usage as well as their psychological and somatic health and socioeconomic factors. Computerized cognitive testing was performed immediately afterward. Additionally, a subsample of 148 volunteers from both study waves was recruited to conduct personal RF-EMF measurements as described in detail for the first study wave ($n = 90$) by Roser et al. (2017). These participants were intentionally sampled depending on their place of residence and school in order to be representative of the entire far-field exposure range of the complete study sample. Participants were required to carry a portable measurement device (exposimeter) with an integrated Global Positioning System (GPS) for 3 consecutive days. Simultaneously, a time–activity app on a smartphone in flight mode had to be filled in to later link the RF-EMF records to a particular activity or place.

Ethical approval for conducting the study was received from the ethical committee of the canton of Lucerne, Switzerland, on 9 May 2012 (EKLU 12025 and EKBB 80/12).

Outcome Assessment: Memory Performance

Cognitive performance was measured using a standardized computerized testing system consisting of the figural and verbal memory subtest of the Intelligenz-Struktur-Test (IST) (Liepmann et al. 2007). For the verbal memory task, participants were given 1 min to memorize five sets of two to five words grouped by their common higher semantic category (e.g., city: Amsterdam, Rome, Hamburg, Madrid, York). The target words were presented by starting with a different letter each time. Immediately after the presenting phase, participants were given a letter and they had to recall the word starting with that letter and report the higher semantic category to which it belonged. This was repeated for 11 words, producing a maximum score of 11 points for the verbal memory task. For the figural memory task, participants were given 1 min to memorize 13 pairs of abstract figures, and immediately afterward one item per pair was shown and participants were asked to choose the correct counterpart out of five possible options. The matching task was repeated for 13 symbols, resulting in a maximum score of 13 points. For each of the two tests, 2 min were given to complete the matching task. Each student started with the verbal memory task.

For the statistical analyses, the difference between the continuous test score values at follow-up minus the baseline values were used as outcome. The coefficient of the outcome–exposure association corresponds directly to the change in score: A positive coefficient thus indicates an improvement in memory between baseline and follow-up in relation to the exposure of interest, whereas a negative association indicates a decrease in memory. In the age group of our study, without considering any exposure, one would generally expect an increase in verbal memory and an increase or little change in figural memory between baseline and follow-up. However, memory development during adolescence may vary largely interindividually (Luciana et al. 2005; Schneider and Pressley 2013).

Exposure: Mobile Phone and General Media Use

The detailed usage of mobile phones and other wireless communication devices was assessed via questionnaire. Questions focused on the average amount and type of mobile phone and media usage per day. Exposures of primary interest were those expected to produce relatively high RF-EMF exposure: specifically, the daily duration and number of calls on mobile and cordless phones. In addition, we asked whether students preferentially held mobile phones on the right or left side of their heads when making calls or whether they had no preference. Further, participants were asked about headset use while calling, which is an important factor for RF exposure because exposure to the body decreases rapidly with increasing distance from the device (Lauer et al. 2013). We also asked about activities that might be correlated with phone use but that would be expected to result in relatively low RF-EMF exposures, including the number of text messages sent per day, daily duration of data traffic on the student's mobile phone, daily duration of gaming on electronic devices, the frequency of social network use, and whether the student's mobile phone was left on or turned off at night. In addition, we used the brief MPPUS-10 scale to assess problematic mobile phone use in the students (Foerster et al. 2015).

For the self-reported usage measures included in the linear regression analysis (daily frequency of text messages, daily duration of mobile phone data traffic, daily duration of gaming, and daily duration of cordless phone use), we calculated the cumulative usage by taking the mean difference between baseline and follow-up, and interpreting this value as usage per day.

Detailed data records of daily quantitative mobile phone use from the 6 months preceding the baseline examination date until the follow-up investigations were obtained from the Swiss mobile phone network operators [Swisscom, Sunrise, and Salt (formerly known as Orange)] if adolescents and one of their parents had given additional written informed consent. These participants are subsequently referred to herein as the operator sample. The operator records included the number and duration of calls, number of text messages sent per day, and the daily volume of data traffic. In addition, the identity of the network (UMTS or GSM) used to start each phone call was obtained from the operators Swisscom and Salt, whereas the third operator, Sunrise, did not provide this information. The daily cumulative mobile phone call duration was calculated by summing up all recorded call durations between baseline and follow-up and dividing this sum by the recorded days between baseline and follow-up to obtain daily usage.

A comparison of self-reported mobile phone use with operator-recorded use indicated severe overestimation of self-reported mobile phone use. To avoid bias, we calibrated self-reported mobile phone call duration for participants without operator records. The calibration equation was derived from the operator sample using a multilevel linear regression model that was clustered by schools with average operator-recorded mobile phone call duration per day as dependent variable and the following predictors to be found relevant (likelihood ratio test for the nonclustered model including or excluding the predictor): age, gender, daily frequency of mobile phone calls at follow-up, daily frequency of text messages at follow-up, daily duration of mobile phone data traffic at follow-up, and daily duration of cordless phone calls at follow-up as well as the difference in daily duration of mobile phone calls between follow-up and baseline (see Table S1). Subsequently, the predicted values from the calibration model were used as estimated daily call duration for the participants without operator data. A similar model was constructed to predict the proportion of calls made on the UMTS network, with the following predictors to be found relevant: the place of residence (urban vs. rural—the UMTS proportion was usually lower in rural areas), UMTS exposure (as a proportion of total downlink) at place of residence obtained by geospatial propagation model (see below), and the number of smartphones at the home as well as the duration of mobile data traffic—all of which were indicators of a higher UMTS proportion. The proportion of GSM network was assumed to be $1-\text{proportion}(\text{UMTS})$. The distinction between both networks used was important in determining RF-EMF exposure because, compared with calls executed on the UMTS network, calls on the GSM network have been associated with irradiation levels heightened by a factor of 100–500 (Gati et al. 2009; Persson et al. 2012). For the participants for whom operator-recorded data was available, the objectively recorded data (cumulative call duration and, if applicable, network proportion) was used for all further analysis, including the RF-dose estimation.

Individual Cumulative RF-EMF Brain Dose

Individual RF-EMF brain dose was calculated using an updated dosimetric model described in detail by Roser et al. (2015) that considers RF-EMF exposure-relevant behaviors and circumstances from near- and far-field sources. Near field refers to the use of RF-EMF–emitting devices close to the body (e.g., mobile phones, wireless Internet), whereas far field refers to the surrounding environmental RF-EMF exposure (e.g., from fixed-site transmitters, W-LAN access points, people using mobile phones nearby).

The first step in dose modeling consists of simulating SARs of the brain gray matter for each exposure-relevant behavior and circumstance [for details see "1. Numeric simulations of brain gray matter specific absorption rates (SAR)" in the Supplemental Material]. SAR is a quantity that indicates the rate at which RF-EMF is absorbed in a certain mass or volume of tissue. SAR values are determined using numeric simulations based on two adolescent human body models from the phantom "virtual population," an 11-y-old girl (Billie) and a 14-y-old boy (Louis) (Gosselin et al. 2014). For near-field sources, SARs were simulated for three scenarios (positions of the emitting device with relation to the body): (*a*) device held close to the ear, (*b*) device kept in the pocket of trousers, and (*c*) device held at a distance of 20 cm to the ear (headset scenario).

SAR values were transformed to dose values by multiplying the SAR with relevant exposure durations (see Table S1). The following near-field exposures were considered in the model: daily duration of mobile phone use (separated by 2G/3G and headset use); daily duration of mobile phone data traffic (separated by transfer via WiFi and mobile phone network); daily duration of cordless phone calls (considering the phone's eco mode if applicable); daily duration of WiFi use on laptop, PC, and tablet; and daily duration of carrying the participant's own mobile phone close to body (e.g., in a pocket). The average output power of these devices was derived from the literature [for details see "1. Numeric simulations of brain gray matter specific absorption rates (SAR)" in the Supplemental Material].

The far-field dose modeling included exposure from mobile phone base stations (downlink) broadcasting (radio and TV), WiFi, DECT (Digital Enhanced Cordless Telecommunications base stations at the home), and far-field exposure from the mobile phones of other nearby people (uplink). Downlink and broadcasting exposure at home and at school was modeled for each participant by means of the geospatial NISMap software (Bürgi et al. 2010).The model is based on accurate operation parameters of all stationary mobile phone and broadcast transmitters and the three-dimensional building and topography model of the study area. Semi-empirical propagation algorithms such as COST-Walfisch-Ikegami (Cichon and Kürner 1999) were used to predict RF-EMF exposure at the receptor points, taking into account, for example, the shielding effects of buildings and topography. Duration of exposure at school was assumed to be 35 h per week in order to eventually obtain the average downlink and broadcasting exposure.

WiFi, uplink, and DECT cannot be modeled by NISMap. Thus, for WiFi and uplink factors, predicting exposure to these sources were identified by linear regression from personal measurement data available from 148 study participants (see Table S1). Relevant predictors for 24-h personal WiFi exposure were the mobile phone operator, presence of WiFi at school, the daily duration of mobile data traffic, and the study wave (2012–2014 vs. 2014–2016). Predictors of uplink were the mobile phone operator, mobile phone status at night (on vs. off), the number of smartphones at the home, the time spent in public transport (train and bus), and the study wave. Because no valuable predictors for DECT could be identified, it was assumed to be the mean DECT exposure as derived from personal measurements in 148 participants. These 24-h far-field exposure values were then transformed to SAR values of the brain gray matter using plane-wave-simulations in the Finite-Different Time-Domain-based simulation software SEMCAD-X, version 16 from SPEAG, Zürich, Switzerland (see Table S2). In a final step, the individual RF-EMF brain gray matter dose for each participant was calculated by summing up the contributions of all different near- and far-field exposure scenarios.

Statistical Analysis

All analyses were conducted for the complete sample as well as separately for the two subsamples investigated during 2012–2014 and 2014–2016, respectively. Following the protocol used in our previous analysis, three different types of exposure variable were considered: (*a*) cumulative RF-EMF brain dose, (*b*) cumulative wireless device use related to RF-EMF exposure (cordless phone calls and mobile phone calls), and (*c*) cumulative wireless device use not or only marginally related to RF-EMF exposure (duration of data traffic, duration of gaming, number of text messages sent). Outcome variables were changes in figural and verbal memory score (follow-up minus baseline) over 1 y.

Separate linear exposure–response models were used to estimate associations between each outcome (the change in verbal or figural memory scores from baseline to follow-up, respectively) and each primary exposure variable (modeled as a continuous variable). All models were adjusted for age, gender, nationality (Swiss, Swiss and other, other), school level [in ascending order according to the school system in Switzerland based on academic expectations: secondary school level C, secondary school level B, secondary school level A, college preparatory high school], frequency of physical activity at follow-up (defined as working out for at least 40 min: ≤1 to 3 times per month, 1 time per week, 2–3 times per week, 4–6 times per week, daily), days of alcohol consumption per month at follow-up (none, ≤1 time per month, 2–4 times per month, 2–3 times per week), change in height between baseline and follow-up (as a proxy for developmental speed between both time points), duration between baseline and follow-up in months, and education of parents (training school, college preparatory high school, college or higher education, university).

In the second step, a laterality analysis of RF-EMF brain dose (head laterality was not considered in the RF-EMF dose model) was conducted given that the figural memory involves mainly the right hemisphere, whereas verbal memory processing is more left sided (Golby et al. 2001; Nagel et al. 2013). Because most of the study participants indicated they held their phone on the right side of their head, we dichotomized the participants into right-side users vs. left-side users and users with no preference (combined). Laterality analyses were performed using data for the entire sample and were repeated after restriction to the operator sample. To facilitate comparisons among the different exposure variables, all effect estimates are expressed as the difference in test scores associated with an interquartile range (IQR) increase in exposure.

Missing values in the confounder variables were either imputed via linear regression (17 missing values at follow-up for alcohol consumption were predicted by age, gender, school class, and school level; 14 missing values at baseline and 12 missing values at follow-up for information on height were predicted by weight, age, and gender) or by imputation, replacing the missing values with the most common category (i.e., 2 missing values at follow-up for frequency of physical activity were replaced by the most common category "2–3 times per week", and 167 missing values for educational level of the parents were replaced by the most common category "Training school"). Statistical analyses were carried out using STATA (version 14; StataCorp).

To evaluate residual confounding from unmeasured factors related to communication device use, we performed stratified analyses across five subgroups representing five different media usage profiles derived by means of latent class analysis of 11 media use variables from the baseline questionnaire data (Foerster and Röösli 2017). The following five classes were identified: Low Use, Medium Use, Call Preference, Gaming, and High Social Use (see Figure S1).

We performed separate linear regression models restricted to students in each of the five media usage groups and estimated differences in each outcome with an IQR increase (defined for the population as a whole) in cumulative RF-EMF brain dose. Next, we performed random effects meta-analyses to derive a summary estimate for each outcome in each subgroup and assessed heterogeneity using the I^2 statistic (Higgins et al. 2003). We assumed that physical effects of RF-EMF would have a similar impact across media use subgroups, independent of any psychological or cognitive effects of media use; therefore, evidence of heterogeneity among the five group-specific estimates would be consistent with uncontrolled psychobehavioral confounding.

Results

In total, 895 adolescents between 12 and 17 y of age were enrolled in the baseline investigation of the HERMES study. The first sampling wave included 439 [mean age ± standard deviation (SD): 14.0 ± 0.85)] students recruited from 57 classes in 24 schools. During the second wave, 456 students (14.1 ± 0.86 y of age) from 44 classes and 22 schools were recruited. A total of 843 participants (96.8% of wave-1 students, $n = 425$; and 91.7% of wave-2 students, $n = 418$) took part in the follow-up investigation 1 y later (Table 1). The average time between baseline and follow-up was 12.5 months. Of these students, 827 (98.1%) owned a mobile phone. The sample included more girls ($n = 457$, 56.4%) than boys ($n = 368$, 43.6%). Objectively recorded operator data for at least 6 months between baseline and follow-up were available for 322 participants (38.8%).

Outcome and Exposure Distributions

Due to technical problems with the computerized testing system, completed tests for both time points were available for only 676 (80.2%) of the participants for verbal memory and 670 (79.5%) for figural memory, respectively (Table 2). While the verbal memory score increased from baseline to follow-up (mean unit increase ± SD = 1.1 ± 3.0), figural memory score did not increase in general (mean increase of 0.2 ± 3.2). The intraclass correlation coefficient (ICC) within individuals was 0.76 for the verbal score, and 0.81 for the figural memory score.

The mean duration of self-reported mobile phone call time was 17.2 ± 27.6 min/d, in contrast with a mean operator-recorded time of 3.2 ± 13.3 min/d. After calibration based on multilevel regression of the subgroup with operator data, the estimated mean mobile phone call time for the sample as a whole was 10.6 ± 13.7 min/d. Mean self-reported cordless phone call duration was 6.2 ± 6.6 min/d (operator data were not available for calibration of cordless phone use). For media exposures associated with low RF-EMF, average daily durations were 56.7 ± 34.3 min/d for mobile phone data traffic and 43.0 ± 56.9 min/d for gaming, and the mean number of text messages sent per day was 35 ± 21.

The estimated mean cumulative RF-EMF brain dose for the population as a whole was 858 ± 1,027 mJ/kg per day when estimated using calibrated mobile phone call durations (mean 10.6 min/d) (Table 2). In the operator data sample ($n = 322$), the estimated mean cumulative RF-EMF brain dose based on recorded call durations (mean 3.2 min/d) was 469 ± 814 mJ/kg per day.

On average, the daily cumulative call duration accounted for 80.3% of the estimated cumulative RF-EMF brain dose in the population as a whole (see Table S3). The proportion for calls executed on the GSM network was much higher (79.8%) compared with the UMTS network (0. 5%). In comparison, when using only data from the operator data sample ($n = 322$), duration of mobile phone use accounted for 66% of estimated cumulative RF-EMF dose (data not shown).

Estimated cumulative RF-EMF brain doses varied among the five media use groups, primarily due to differences in mobile phone call duration (Table 2; see also Figure S1). For example, the Call Preference group ($n = 119$), which had calibrated daily mobile phone and cordless call duration estimates of 15.9 ± 11.9 and 10.8 ± 9.6 min/d, respectively, had a mean estimated daily RF-EMF brain dose of 1,214 ± 1,259 mJ/kg per day, compared with 551 ± 1,029 mJ/kg per day for the Low Use group ($n = 198$), mean calibrated mobile and cordless phone call duration estimates of 5.9 ± 7.7 and 6.0 ± 5.6 min/d, respectively.

Associations between Changes in Memory Performance and RF-EMF Dose and Media Usage

In the population as a whole, none of the exposure variables were significantly associated ($p < 0.05$) with changes in verbal memory scores (Table 3, Figure 1). However, there was a nonsignificant association with the cumulative duration of data traffic and the increase in verbal memory score [score change per IQR: 0.34; 95% confidence interval (CI): −0.05, 0.72; IQR: 55.4 min/d], which was consistent over both study waves (Figure 2).

Table 1. Distributions among different sociodemographic and lifestyle variables for all participants taking part in the follow-up investigations and the five media use groups separately.

Characteristic	Total [n (%)][a]	Gamer [n (%)][a]	Media use[b] [n (%)][a]	Low use [n (%)][a]	Call preference [n (%)][a]	High social use [n (%)][a]
n (total)	843 (100)	97 (12)	223 (26)	207 (25)	119 (14)	197 (23)
Age [y (min–max)]	14.0 (10.3–17.0)	14.1 (12.2–16.4)	13.9 (10.4–17.0)	13.8 (11.8–15.8)	14.3 (12.3–16.6)	14.1 (12.5–16.1)
Sex						
Female	475 (56.4)	96 (99.0)	102 (45.7)	90 (43.5)	32 (26.9)	48 (24.4)
Male	368 (43.6)	1 (1.0)	121 (54.3)	117 (56.5)	87 (73.1)	149 (75.6)
Sample						
Sample 1 (2012–2013)	425 (50.4)	40 (41.2)	51 (22.9)	191 (92.3)	118 (99.2)	25 (12.7)
Sample 2 (2014–2015)	418 (49.6)	57 (58.8)	172 (77.1)	16 (7.7)	1 (0.8)	172 (87.3)
Nationality						
Swiss	646 (76.6)	75 (77.3)	175 (78.5)	174 (84.1)	89 (74.8)	133 (67.5)
Swiss and foreign	120 (14.2)	11 (11.3)	31 (13.9)	25 (12.1)	19 (16)	34 (17.3)
Foreign	77 (9.2)	11 (11.3)	17 (7.6)	8 (3.9)	11 (9.2)	30 (15.2)
School level[c]						
Secondary school level C	151 (17.9)	23 (23.7)	30 (13.5)	22 (10.6)	34 (28.6)	42 (21.3)
Secondary school level B	242 (28.7)	36 (37.1)	69 (30.9)	43 (20.8)	30 (25.2)	64 (32.5)
Secondary school level A	272 (32.3)	20 (20.6)	68 (30.5)	80 (38.7)	41 (34.5)	63 (32)
High school level	178 (21.1)	18 (18.6 %)	56 (25.1)	62 (30)	14 (11.8)	28 (14.2)
Highest education of the parents[d]						
Training school	496 (58.8)	58 (59.8)	129 (57.9)	88 (42.5)	73 (61.3)	148 (75.1)
College preparatory high school	50 (5.9)	6 (6.2)	15 (6.7)	14 (6.8)	4 (3.4)	11 (5.6)
College of higher education	235 (27.9)	22 (22.7)	63 (28.3)	81 (39.1)	37 (31.1)	32 (16.2)
University	62 (7.4)	11 (11.3)	16 (7.2)	24 (11.6)	5 (4.2)	6 (3.1)
Physically active (FUP)[e]						
≤1 to 3 times per month	128 (15.2)	11 (11.3)	30 (13.5)	28 (13.5)	19 (16)	40 (20.4)
1 time per week	170 (20.2)	16 (16.5)	39 (17.5)	43 (20.8)	31 (26.1)	41 (20.9)
2–3 times per week	316 (37.4)	40 (41.2)	81 (36.3)	83 (40.1)	43 (36.1)	68 (34.7)
4–6 times per week	159 (18.9)	21 (21.7)	48 (21.5)	36 (17.4)	18 (15.1)	36 (18.4)
Daily	70 (8.3)	9 (9.3)	25 (11.2)	17 (8.2)	8 (6.7)	11 (5.6)
Number of days with alcohol consumption (FUP)[f]						
None	469 (55.6)	47 (48.5)	138 (61.9)	142 (68.6)	48 (40.3)	94 (47.7)
≤1 time per month	200 (23.7)	28 (28.9)	51 (22.9)	41 (19.8)	35 (29.4)	45 (22.8)
2–4 times per month	139 (16.5)	13 (13.4)	32 (14.4)	19 (9.2)	29 (24.4)	46 (23.4)
2–3 times per week	35 (4.2)	9 (9.3)	2 (0.9)	5 (2.4)	7 (5.9)	12 (6.1)
Change in height (cm ± SD) (follow-up–baseline)[g]	3.7 ± 6.7	5.8 ± 4.1	4.4 ± 4.4	4.4 ± 4.8	1.2 ± 13.7	2.5 ± 3.9

Note: FUP, follow-up; max, maximum value; min, minimum value; SD, standard deviation.
[a]Numbers are n (%) unless notes otherwise.
[b]Media use groups determined by latent class analysis on 11 qualitatively different media use variables as described in Foerster and Röösli (2017).
[c]According to the school system in Switzerland, school levels imply differing academic expectations (in ascending order: secondary school level C, secondary school level B, secondary school level A, college preparatory high school); 167 missing values for educational level of the parents replaced by the most common category "Training school."
[d]Highest level of education achieved by at least one of the parents.
[e]Physical activity defined as working out at least 40 min with perspiration; two values missing at follow-up for frequency of physical activity were replaced by the most common category "2–3 times per week."
[f]Seventeen values missing at follow-up for alcohol consumption were imputed via linear regression imputation predicted by age, gender, school class, and school level.
[g]Fourteen values missing at baseline and 12 values missing at follow-up for information on height were predicted by weight, age, and gender.

Changes in figural memory score were negatively correlated with cordless phone calls and, in tendency, with the duration of mobile phone calls and the cumulative RF-EMF brain dose (Figure 2). The association with RF-EMF brain dose was nonsignificant in the full sample (−0.22 (95% CI: −0.47, 0.03; IQR: 953 mJ/kg per day) and significant in the operator data sample (−0.26 (95% CI: −0.42, −0.10; IQR: 341 mJ/kg per day). When analyzing the two subsamples separately, for both study waves, nonsignificant negative effect estimates for the RF-EMF dose were seen, although the magnitude of this effect was greater for the second ($n = 288$) compared with the first wave ($n = 375$) but with a wider confidence interval for the second wave (first wave: −0.14 (95% CI: −0.42, 0.14); second wave: (−0.58 (95% CI: −1.17, 0.01); IQR: 953 mJ/kg per day). No association was observed with variables that were only marginally related to RF-EMF exposure (cumulative duration of data traffic, cumulative gaming duration, and cumulative number of text messages).

The association between figural memory score and cumulative brain dose became significant when analysis was restricted to users with right-side preference (full sample: $n = 532$; operator sample: $n = 217$) in the laterality analysis (full sample: −0.38; 95% CI: −0.67, −0.09; IQR: 953 mJ/kg per day; operator sample: −0.29 (95% CI: −0.46, −0.11; IQR: 341 mJ/kg per day) (Figure 3). When restricted to left-side/no-preference users, the effect estimates were, in general, imprecise due to the small sample size (full sample: $n = 137$; operator sample: $n = 57$). However, a significant negative association was found for verbal memory in the operator sample (−0.51; 95% CI: −0.89, −0.13; IQR: 341 mJ/kg per day).

Meta-Analysis over Media Use Groups

The pooled random effects estimate for the association between cumulative brain dose and figural memory score over the five media use groups (−0.39; 95% CI: −0.69, −0.09; IQR: 953 mJ/kg per day) was consistent with the main analysis, and did not support heterogeneity among the groups ($I^2 = 0.0\%$). The pooled effect for verbal memory score was 0.02 (−0.24, 0.31; IQR: 953 mJ/kg per day; $I^2 = 0.0\%$) (see Figure S2).

Discussion

In the present study, an IQR increase in estimated cumulative RF-EMF brain dose was associated with a nonsignificant decrease in figural memory score, but was not associated with verbal memory

Table 2. Descriptive statistics for all different exposure variables used in linear regression models for the whole sample and the five media use groups separately.

Variable	Total			Low use			Media use[a]			Gaming			Call preference			High social use		
	n	mean ± SD	IQR[b]	*n*	mean ± SD	IQR	*n*	mean ± SD	IQR	*n*	mean ± SD	IQR	*n*	mean ± SD	IQR	*n*	mean ± SD	IQR
Whole sample																		
Verbal memory score[c]																		
Baseline	751	4.9 ± 2.8	4.0	196	5.3 ± 2.7	3.5	191	4.8 ± 2.7	4.0	88	4.8 ± 2.8	3.5	110	4.8 ± 2.8	4.0	166	4.6 ± 3.0	5.0
Follow-up	738	5.9 ± 2.7	4.0	187	6.5 ± 2.6	5.0	193	5.9 ± 2.8	4.0	84	5.5 ± 2.7	4.0	110	5.8 ± 2.8	4.0	164	5.6 ± 2.8	4.0
Difference (follow-up–baseline)	676	1.1 ± 3.0	4.0	180	1.3 ± 2.9	4.0	168	1.0 ± 3.0	4.0	78	0.8 ± 2.7	3.0	106	1.2 ± 2.9	4.0	144	1.2 ± 3.3	4.5
Figural memory score[a]																		
Baseline	740	7.8 ± 2.8	4.0	195	8.5 ± 2.5	3.0	189	7.3 ± 2.8	4.0	86	6.9 ± 2.7	4.0	110	8.1 ± 2.7	4.0	160	7.6 ± 3.1	4.0
Follow-up	742	7.9 ± 3.3	6.0	189	8.5 ± 3.2	5.0	194	8.0 ± 3.2	5.0	85	6.8 ± 3.5	6.0	110	7.5 ± 3.3	5.0	164	7.7 ± 3.5	6.0
Difference (follow-up–baseline)	670	0.2 ± 3.2	4.0	180	0.1 ± 2.8	4.0	168	0.7 ± 3.0	4.0	77	−0.3 ± 3.6	6.0	106	−0.5 ± 3.2	5.0	139	0.5 ± 3.6	5.0
Usage related to EMF exposure to the head																		
Cordless phone calls [min/d]	843	6.2 ± 6.6	5.1	207	6.0 ± 5.6	5.1	223	4.7 ± 4.1	4.0	97	4.0 ± 3.6	2.3	119	10.8 ± 9.6	11.3	197	6.5 ± 7.6	5.1
Mobile phone calls [min/d][d]	843	10.6 ± 13.7	12.6	207	5.9 ± 7.7	7.4	223	9.0 ± 12.8	10.2	97	9.9 ± 12.3	15.7	119	15.9 ± 11.9	13.2	197	14.4 ± 18.4	15.3
Mobile phone calls, self-reported [min/d]	843	17.2 ± 27.6	16.3	207	7.3 ± 10.9	7.0	223	11.4 ± 19.1	9.9	97	13.8 ± 34.5	9.4	119	31.1 ± 35.8	27.5	197	26.7 ± 32.1	27.4
Usage marginally related to EMF exposure to the head																		
Data traffic [min/d]	843	56.7 ± 34.3	55.4	207	27.6 ± 25.2	35.5	223	51.3 ± 28.3	43.4	97	59.2 ± 30.5	44.7	119	66.7 ± 26.5	41.4	197	86.1 ± 27.3	44.8
Gaming [min/d]	843	43.0 ± 56.9	55.7	207	38.6 ± 48.6	51.3	223	20.9 ± 33.9	29.3	97	116.1 ± 63.2	63.6	119	49.6 ± 62.0	56.8	197	32.7 ± 50.2	40.0
Texts sent [number/d]	843	35 ± 21	40	207	15 ± 12	17	223	32 ± 18	30	97	36 ± 20	35	119	43 ± 17	24	197	54 ± 12	13
Cumulative brain dose [mJ/kg per day][e]	830	858 ± 1,027	953	198	551 ± 1,029	471	221	753 ± 824	800	97	806 ± 956	997	118	1,214 ± 1,259	1,391	196	1,098 ± 1,003	1,110
Sample with operator data																		
Duration mobile phone calls [min/d]	322	3.2 ± 13.3	1.8	116	1.1 ± 2.9	0.8	63	4.2 ± 4.1	1.7	30	1.7 ± 3.1	1.2	65	2.8 ± 3.8	2.7	48	8.8 ± 29.2	8.0
Cumulative brain dose [mJ/kg per day][e]	318	469 ± 814	341	115	357 ± 918	187	61	465 ± 638	324	30	344 ± 694	152	65	620 ± 793	517	47	607 ± 842	443

Note: EMF, electromagnetic field; IQR, interquartile range; SD, standard deviation.
[a]Media use groups were determined by latent class analysis on 11 qualitatively different media use variables as described in Foerster and Röösli (2017).
[b]User-group–specific IQRs are displayed for descriptive purposes. For reporting user-group–specific IQRs (see Figure S2), the whole population IQR was used.
[c]Due to technical problems with the computerized testing system, completed tests for both time points were only available for a reduced number of participants.
[d]Adjusted via multilevel linear regression estimates calibrated on the objectively recorded duration of calls obtained by mobile phone operators. Models were clustered over schools and the following predictors were selected from the self-reported questionnaire data: age, gender, daily frequency of mobile phone calls at follow-up, daily frequency of text messages at follow-up, daily duration of mobile phone data traffic at follow-up, daily duration of cordless phone calls at follow-up, difference in daily duration of mobile phone calls between follow-up and baseline.
[e]Cumulative brain dose derived based on the following cumulative exposure variables. Near-field bands (if not indicated otherwise, taken from the questionnaire): daily duration of mobile phone calls (for the whole sample: calibrated via operator data; for the operator sample: operator recorded), network proportions of UMTS and GSM (for the whole sample: calibrated via operator data and far-field UMTS proportion; for the operator sample: operator recorded), proportion of headset use, daily duration of cordless phone calls, daily duration of mobile phone data traffic on WiFi and 3G, daily duration of WiFi use via laptop, PC, and tablet, daily duration of mobile phone held close to body; far-field bands: Uplink from surrounding mobile phones and Wifi (modeled via linear regression estimation based on questionnaire and personal measurements), downlink GSM900, downlink GSM1800, downlink UMTS, radio/broadcast, TV [(determined by geospatial propagation modeling using the NISMap software (Bürgi et al. 2010)], DECT (mean of the measurements).

Table 3. Results of adjusted linear exposure models for the whole sample and the two subsamples (2012–2014 and 2014–2016).

Exposure	n	IQR	Whole sample [adjusted[a] (95% CI)]	n	Sample 2012–2014 [adjusted[a] (95% CI)]	n	Sample 2014–2016 [adjusted[a] (95% CI)]
Whole sample							
Usage related to EMF exposure to the head							
Verbal memory							
Cordless phone calls [min/d]	676	5.1	−0.02 (−0.20, 0.15)	375	−0.05 (−0.26, 0.15)	301	−0.10 (−0.46, 0.25)
Mobile phone calls [min/d][b]	676	12.6	−0.01 (−0.29, 0.27)	375	0.08 (−0.31, 0.46)	301	−0.15 (−0.57, 0.26)
Figural memory							
Cordless phone calls [min/d]	670	5.1	−0.23 (−0.42, −0.04)	381	−0.23 (−0.45, −0.02)	289	−0.21 (−0.64, 0.22)
Mobile phone calls [min/d][b]	670	12.6	−0.21 (−0.51, 0.09)	381	0.01 (−0.40, 0.41)	289	−0.44 (−0.90, 0.02)
Cumulative brain dose [mJ/kg per day][c]							
Verbal memory	675	953	0.02 (−0.22, 0.26)	372	0.01 (−0.26, 0.27)	293	0.03 (−0.52, 0.58)
Figural memory	669	953	−0.22 (−0.47, 0.03)	381	−0.14 (−0.42, 0.14)	288	−0.58 (−1.17, 0.01)
Usage marginally related to EMF exposure to the head							
Verbal memory							
Data traffic [min/d]	676	55.4	0.34 (−0.05, 0.72)	375	0.48 (−0.04, 1.00)	301	0.33 (−0.28, 0.94)
Gaming [min/d]	676	55.7	−0.03 (−0.30, 0.25)	375	0.04 (−0.33, 0.40)	301	−0.16 (−0.59, 0.27)
Texts sent (units/d)	676	40	0.16 (−0.31, 0.63)	375	0.40 (−0.21, 1.02)	301	0.00 (−0.75, 0.75)
Figural memory							
Data traffic [min/d]	670	55.4	−0.05 (−0.46, 0.37)	381	0.18 (−0.37, 0.73)	289	−0.47 (−1.14, 0.21)
Gaming [min/d]	670	55.7	−0.12 (−0.41, 0.17)	381	0.02 (−0.36, 0.41)	289	−0.36 (−0.83, 0.12)
Texts sent (units/d]	670	40	0.04 (−0.45, 0.54)	381	0.20 (−0.45, 0.84)	289	−0.22 (−1.05, 0.62)
Sample with operator data							
Verbal memory							
Mobile phone calls [min/d]	277	1.8	−0.01 (−0.10, 0.08)	210	0.15 (−0.06, 0.37)	67	−0.01 (−0.13, 0.11)
Cumulative brain dose [mJ/kg per day][c]	273	341	0.02 (−0.14, 0.18)	209	0.05 (−0.12, 0.21)	64	−0.30 (−1.04, 0.44)
Figural memory							
Mobile phone calls [min/d]	278	1.8	−0.03 (−0.12, 0.06)	212	−0.18 (−0.39, 0.04)	66	0.03 (−0.11, 0.16)
Cumulative brain dose [mJ/kg per day][c]	274	341	−0.26 (−0.42, −0.10)	211	−0.25 (−0.41, −0.09)	63	−0.35 (−1.20, 0.50)

Note: Coefficients relate to change score per IQR of exposure shown in the column "IQR." CI, confidence interval; EMF, electromagnetic field.
[a]All models adjusted for age, gender, school level, education of the parents, alcohol consumption at follow-up, physical activity at follow-up, change in height (follow-up–baseline) and time between baseline and follow-up.
[b]Self-reported use calibrated with the objectively recorded duration of calls as described in Table S1.
[c]Cumulative brain dose derived based on the following cumulative exposure variables. Near-field bands (if not indicated otherwise, taken from the questionnaire): daily duration of mobile phone calls (for the whole sample: calibrated via operator data; for the operator sample: operator recorded), network proportions of UMTS and GSM (for the whole sample: calibrated via operator data and far-field UMTS proportion; for the operator sample: operator recorded), proportion of headset use, daily duration of cordless phone calls, daily duration of mobile phone data traffic on WiFi and 3G, daily duration of WiFi use via laptop, PC, and tablet, daily duration of mobile phone held close to body; far-field bands [if not indicated otherwise, exposure was determined by geospatial propagation modeling using the NISMap software (Bürgi et al. 2010)]: Uplink from surrounding mobile phones (modeled via linear regression estimation based on questionnaire and personal measurements), downlink GSM900, downlink GSM1800, downlink UMTS, WiFi (modeled via linear regression estimation based on questionnaire and personal measurements), radio/broadcast, TV, DECT.

score. This inverse association of cumulative RF-EMF brain dose was consistently seen in the full sample analysis and the subgroup analysis of the two study waves (2012–2014 vs. 2014–2016), media usage groups, and the operator sample although the strength of the association differed somewhat. The association was stronger in the second than in the first wave (however, with a wider confidence interval) and statistically significant in the operator sample, but not in the whole sample with self-reported exposure (after calibration using operator data). A significant decrease in figural memory score with cumulative brain dose was further seen in laterality analysis for right-side users of both the full sample and the operator sample only. In left-side users, in contrast, we found a significant decrease in verbal memory score for the operator sample. However, there was no such association for the full sample and estimates for the left-side users were in general imprecise due to the small sample size and also less consistent. The more consistent association of right-side users with a decrease for figural memory and the decrease for verbal memory score seen in left-side users of the operator sample might be related to the lateralization of memory processes (Golby et al. 2001) and requires further study.

Regarding wireless media usage not related to high RF-EMF exposure, a nonsignificant positive association for cumulative duration of mobile phone data traffic and verbal memory score change was observed, whereas the coefficients for text messages and gaming were generally small. It is conceivable that a positive significant association of verbal memory and data traffic could cover a potential negative RF-EMF effect on verbal memory if data traffic and RF-EMF dose are highly correlated. To control for this, we post hoc calculated the Spearman's correlation and fitted a regression model on verbal memory including both variables and adjusted for the same confounding variables as before. Spearman's correlation was weak ($\rho = 0.25$), and the linear regression estimates for neither RF-EMF dose nor duration of data traffic changed majorly in the mutually adjusted model (data not shown).

Strengths and Limitations

The present study is unique in its approach to overcoming the main challenges in epidemiological research on RF-EMF. We estimated individual RF-EMF brain doses for the population as a whole using objectively recorded operator data from a subset of participants to calibrate self-reported call duration and thus reduce misclassification. The operator-recorded data allowed us to estimate the very exposure-relevant proportion of calls on the GSM and UMTS networks (Erdreich et al. 2007; Gati et al. 2009). In our sample, the respective brain dose contributions were 79.8% (GSM) and 0.5% (UMTS) (see Table S2).

The modeling allowed addressing the associations with mobile phone use and RF-EMF brain dose separately to evaluate potential residual confounding of lifestyle and media use related to wireless device use itself. These factors might act on human health, cognition, and behavior independently from a potential biological radiation effect (Kuss et al. 2014; Kuss and Griffiths 2011, 2012; Roser et al. 2016). To control for such confounding, we adjusted our analysis for age, gender, school level, parents' education, alcohol consumption, and physical activity at follow-up, and the time and change in height between baseline and

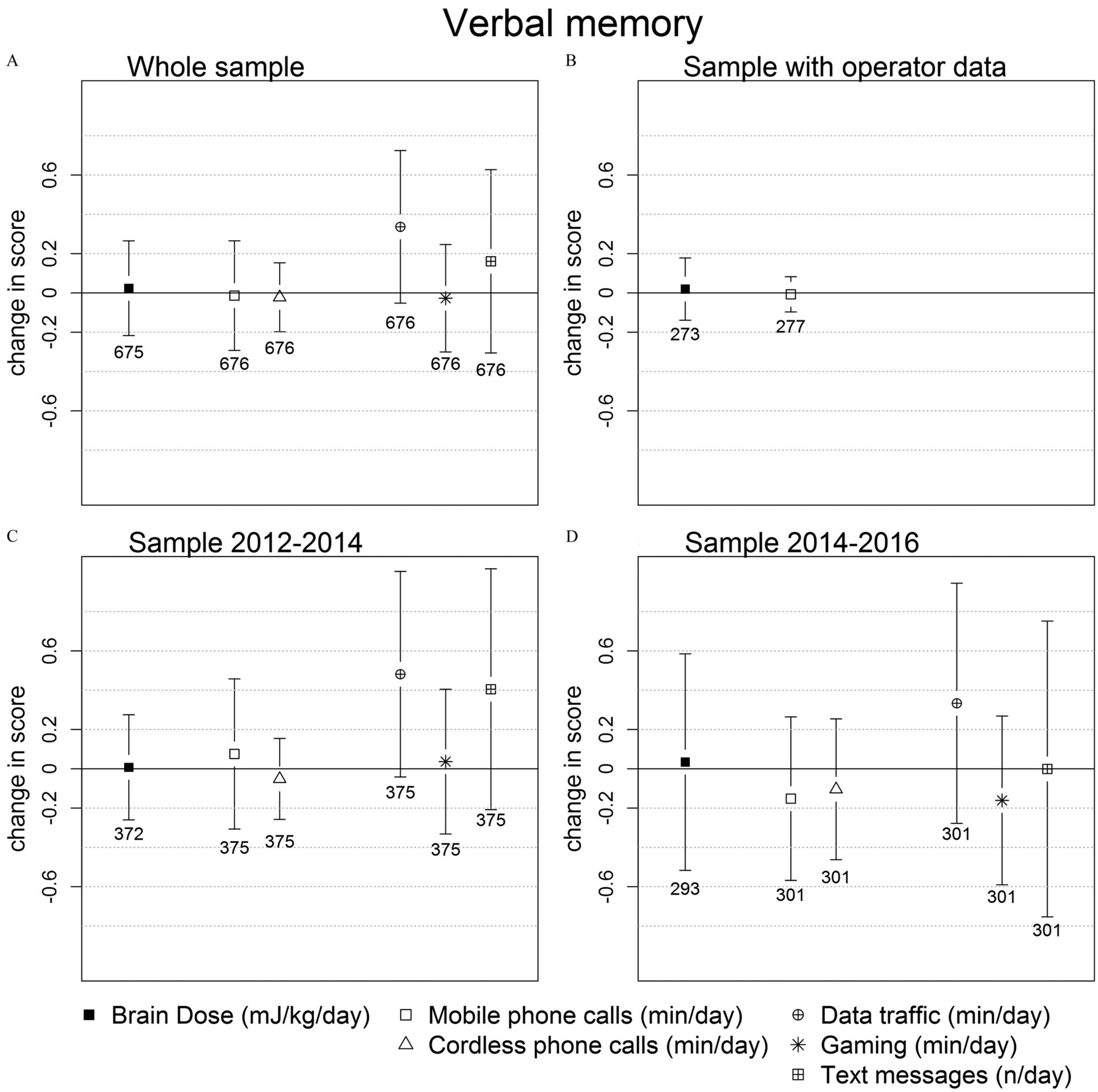

Figure 1. Results of linear exposure–response models for change in verbal memory scores (follow-up–baseline): estimates relate to change in memory score for (*A*) the whole sample per interquartile range (IQR) of exposure of the whole sample; (*B*) the operator sample per IQR of operator sample; (*C*) the sample 2012–2013 per IQR of exposure of the whole sample; and (*D*) the sample 2014–2015 per IQR of exposure of the whole sample. IQRs of the whole sample: brain dose, 953 mJ/kg per day; mobile phone calls, 12.6 min/d; cordless phone calls, 5.1 min/d; data traffic, 55.4 min/d; gaming, 55.7 min/d; and text messages, 40 per day. IQRs of the operator data, brain dose: 341 mJ/kg per day; and mobile phone calls, 1.8 min/d. All models were adjusted for age, gender, baseline score, nationality, school level, physical activity, alcohol, and education of parents and change in height and time between baseline and follow-up investigation. Number of observations for each calculation is indicated below each estimate.

follow-up. In addition, we estimated associations with media exposures associated with low RF-EMF exposures (minutes of gaming, minutes of mobile phone data traffic, and numbers of texts sent each day) to assess the potential impact of media use unrelated to RF-EMF.

In addition, we applied a new approach to control for residual confounding by stratifying the analysis for the RF-EMF brain dose over independent patterns of media use. Separate estimates for students classified according to the five media use patterns were similar among the groups for both verbal and figural memory, with I^2 statistics indicating little or no heterogeneity, and pooled estimates were consistent with estimates based on the main analysis. This pattern does not support major bias from uncontrolled confounding and is compatible with associations due to biophysical effects of RF-EMF, rather than effects of media use unrelated to RF-EMF. However, sample sizes within the five media use groups were small, and residual confounding cannot be ruled out based on this analysis.

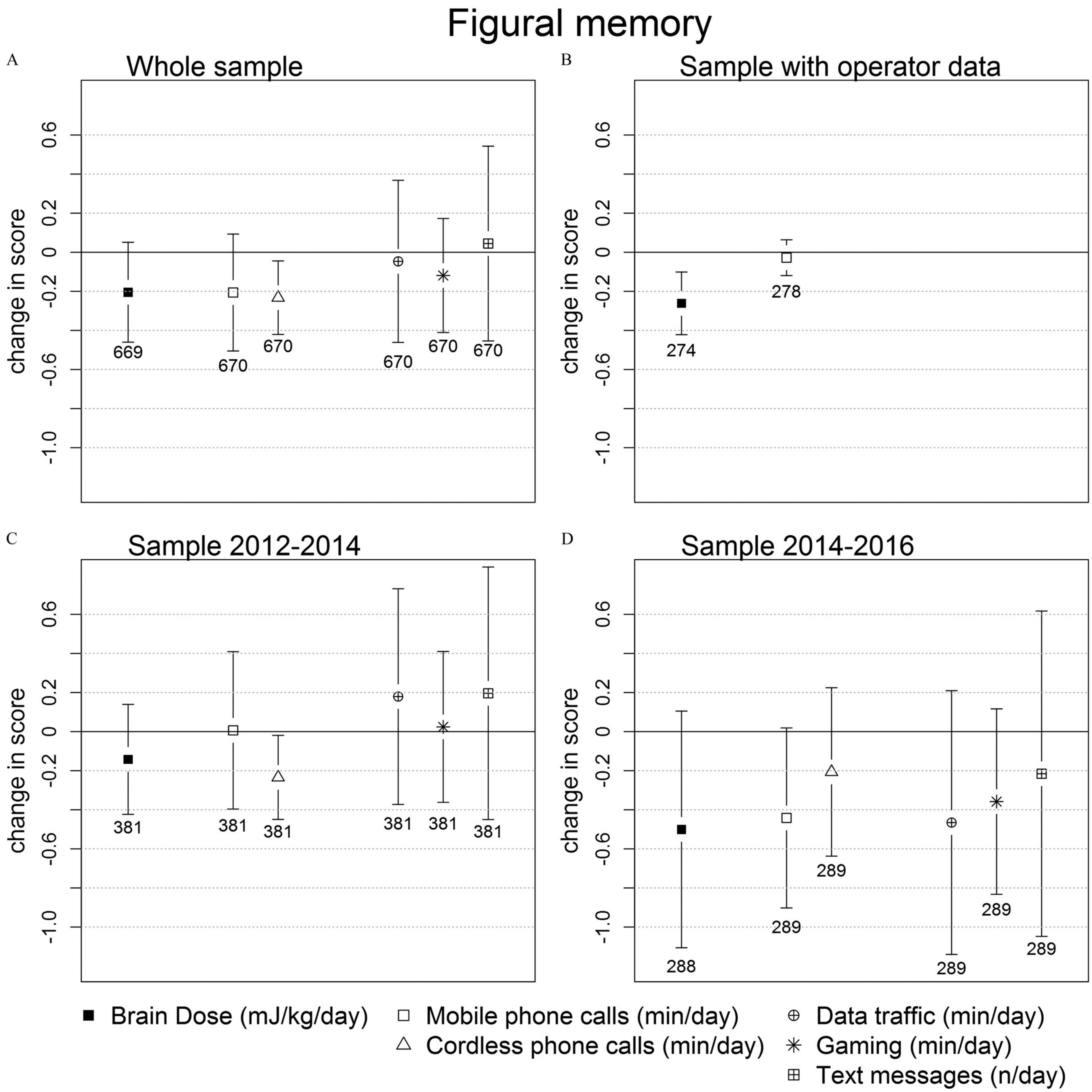

Figure 2. Results of linear exposure–response models for change in figural memory scores: (follow-up–baseline estimates relate to change in memory score for (*A*) the whole sample per interquartile range (IQR) of exposure of the whole sample; (*B*) the operator sample per IQR of operator sample; (*C*) the sample 2012–2013 per IQR of exposure of the whole sample; and (*D*) the sample 2014–2015 per IQR of exposure of the whole sample. IQRs of the whole sample: brain dose, 953 mJ/kg per day; mobile phone calls, 12.6 min/d; cordless phone calls, 5.1 min/d; data traffic, 55.4 min/d; gaming, 55.7 min/d; and text messages, 40 per day. IQRs of the operator data: brain dose, 341 mJ/kg per day; and mobile phone calls, 1.8 min/d. All models were adjusted for age, gender, baseline score, nationality, school level, physical activity, alcohol, and education of parents and change in height and time between baseline and follow-up investigation. Number of observations for each calculation is indicated below each estimate.

This study put a lot of emphasis on the exposure assessment and dose calculation. Information for the far-field exposure was retrieved from propagation models (Bürgi et al. 2010) and from personal measurements in 148 children (Roser et al. 2017). Operator-recorded mobile phone data is an asset, and, to our knowledge, it has not been available for other epidemiological studies of children and adolescents. Although operator data are objectively recorded, they have a disadvantage in that calls on other people's phones are not recorded. Furthermore, information on short message services does not represent texting behavior of adolescents using mostly Internet-based applications such as WhatsApp, and besides, the duration of data traffic and cordless phone use was not available from the operator. Thus, for these variables, the corresponding self-reported data had to be used for dose estimation as in the operator sample.

Uncertainty in the exposure assessment and in the RF-EMF dose calculations cannot be avoided. Estimation of SAR assumes a typical distance between emitting devices and body and average

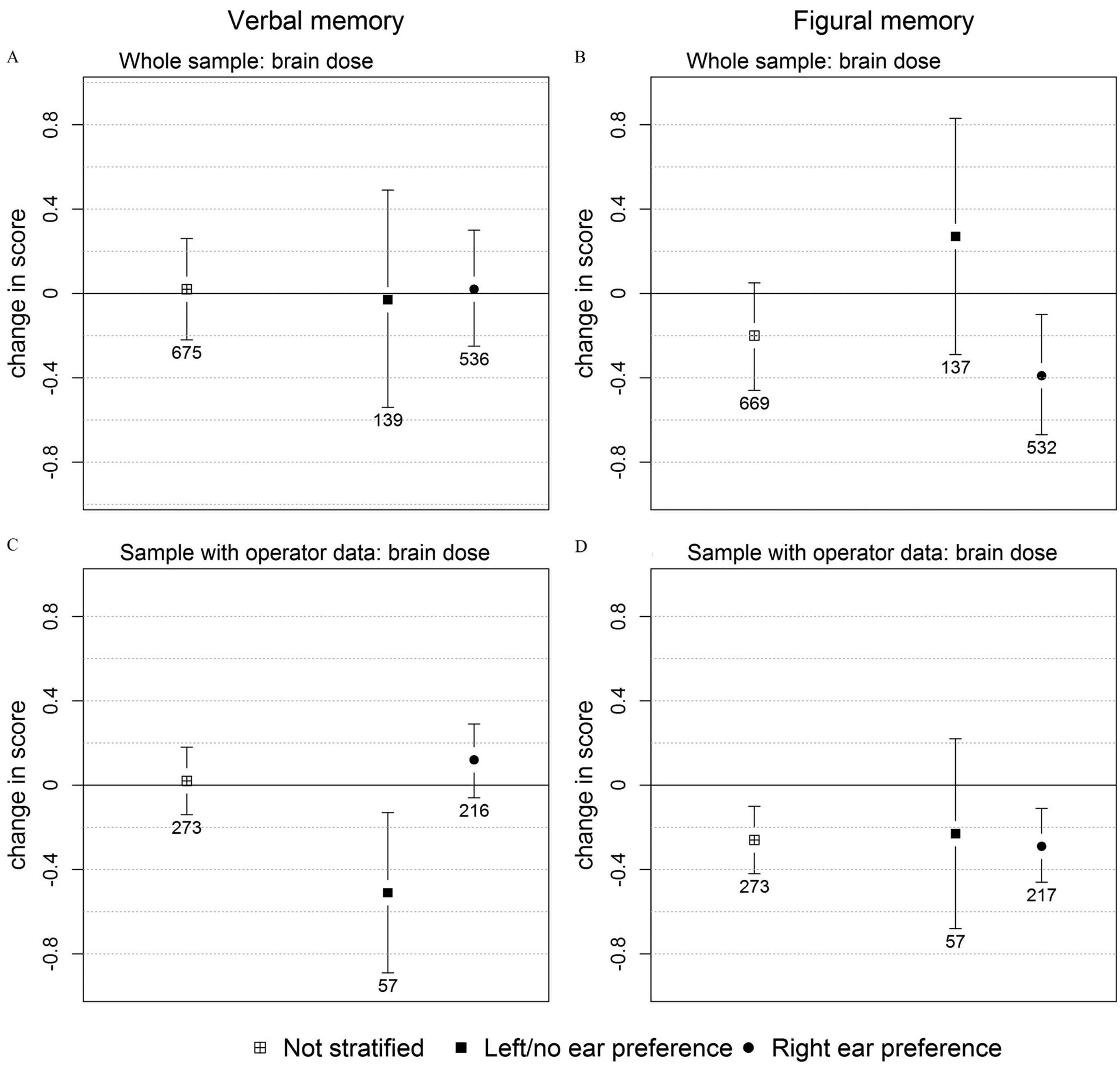

Figure 3. Results of the laterality analysis for the adjusted linear exposure response for the brain dose on changes in verbal and figural memory scores of the Intelligenz-Struktur-Test (IST). Estimates relate to (*A*) change in verbal memory score per interquartile range (IQR) of exposure for the whole sample; (*B*) change in figural memory score per IQR of exposure for the whole sample; (*C*) change in verbal memory score for the operator sample per IQR of the operator sample; and (*D*) change in figural memory score for the operator sample per IQR of the operator sample. Brain dose was derived via individual exposure modeling of relevant near- and far-field exposure sources. The most relevant predictors—duration of mobile phone calls and network proportion—were derived directly by network operators for the operator data sample. For the whole sample, these parameters were calibrated via multilevel linear regression models, predicting these parameters by self-reported questionnaire data, fitted for the operator sample. Change in memory score per IQR range of exposure. IQR for the whole sample, 953 mJ/kg per day; and IQR for the operator sample, 341 mJ/kg per day.

absorption characteristics of the body. But all of these aspects are variable in reality. A validation study could not be confirmed given than dose is not directly measurable and can only be computed.

Our study participants were recruited from the four common public school levels in urban and rural areas of Switzerland. Neither private nor religious schools were included because they play a minor role in Switzerland. All schools were located in Swiss German-speaking cantons, although Switzerland also has large French-, Italian-, and Rhaeto- Romanic-speaking areas. Generalizability might thus be restricted to public schools in German-speaking Switzerland. However, because RF-EMF brain dose is a biological measure, the exposure route should not differ among adolescents in general. Loss to follow-up was low (5.8%), but selection bias cannot be ruled out given that participation rates at baseline were only 37% for the first-wave (2012–2014) but 56% for the second-wave (2014–2016) study samples.

Comparison with Previous Analysis

The association between memory and RF-EMF exposure in the 2012–2014 sample has been analyzed previously (Schoeni et al. 2015). In the present work, we applied an improved RF-EMF dose estimation to the whole HERMES sample. The Spearman's correlation between the resulting new RF-EMF brain dose and the former dose estimate in the 2012–2014 sample was $\rho = 0.58$, demonstrating inherent uncertainties in dose estimation. The main difference compared with the previous dose modeling (Roser et al. 2015) was the use of operator calibrated self-reported call duration and different SAR values. Our new estimate of the first sample wave was of similar magnitude but less significant [-0.14 (-0.42, 0.14) per IQR of 953 mJ/kg per day] than in the previous analysis reported by Schoeni et al. (2015) [-0.26 (95% CI: -0.42, -0.10) per IQR of 1,579 mJ/kg per day].

Compared with the previous analyses, we have improved the dose calculations by various aspects. First, in the previous study, self-reported mobile phone use data was used for the dose calculation. It is well known that adolescents tend to overestimate duration of use and that the extent of overestimation is related to various sociodemographic factors (Aydin et al. 2011). This time, we used operator-recorded mobile phone data to adjust self-reported mobile phone use in order to reduce the overestimation of self-reported use. Consecutively, this led to a lower average RF-EMF dose estimation that might be closer to reality. The calibration was based on the assumption, that the factor and pattern by which participants overestimate their use could be extrapolated from the operator data sample. However, it must be noted that a large majority (approximately 75%) of the operator sample were participants from the first study wave. This might affect the generalizability of the operator sample–based estimates to the sample as a whole, in particular if relationships among self-reported variables considered for calibration and the operator-recorded data would be different for the first and second study wave due to increasing dissemination of smartphones in the study sample and the expansion of the UMTS network in the study region. However, differences in media usage behavior between the study waves might be more related to smartphone-specific applications rather than mobile phone calls (Foerster and Röösli 2017). Second, in the framework of the EU project GERoNiMO (Generalized EMF Research using Novel MethOds), new SAR estimates have been computed for various near- and far-field exposure conditions. Most relevant, these SAR estimates are based on the adolescent models Billie and Louis from the virtual population [for details see "1. Numeric simulations of brain gray matter specific absorption rates (SAR)" in the Supplemental Material], whereas in the past only SAR calculations from adult phantoms were available.

Brain Exposure and Differential Memory-Related Neuronal Circuits

Our findings require confirmation in other populations but suggest that RF-EMF brain exposure may have an adverse effect on figural memory functions in adolescents. The decrease in figural memory score with an IQR increase in exposure was 0.22 (95% CI: -0.47, 0.03; IQR: 953 mJ/kg per day) in the full sample ($n = 669$) and 0.26 (95% CI: -0.42, -0.10; 341 mJ/kg per day) in the operator sample ($n = 274$). To put this difference into context, in our main model adjusting for various factors, we observed a mean difference in figural memory score of 0.41 (95% CI: 0.13, 0.69) between adolescents from a lower school level (e.g., secondary school level C) to the next higher one (i.e., secondary school level B). Memory functions continue to develop in adolescents, and the ability to maintain and manipulate multiple spatial units (which is tested by the figural memory task) continues to develops until 15 y of age (Luciana et al. 2005).

Different brain areas and activation patterns are involved in neural memory processing, which is measured by different cognitive tests. Due to the differing specificity of cognitive tests, results often cannot be compared directly. Although we found decreases in figural memory, some experimental and epidemiological studies on RF-EMF found improvements in working memory performance. Working memory is usually assessed via reaction time tasks such as the *n*-back paradigm, where participants need to react in an accurate manner on a stimulus after a short time interval as fast as possible. This type of memory is also known as working attention and is related to very early stages of memory where stimuli are held actively in mind before being stored (Baddeley and Hitch 1974). For working memory, main brain activity is seen in executive structures involved in decision-making, predominantly the anterior cingulate and dorsolateral and inferior prefrontal cortices (Jansma et al. 2000). In addition to voluntary encoding, the memory processes evaluated in our study require consolidation (storage) of a stimulus and its subsequent recognition (retrieval) after a short period of time. In these later stages of memory, the activation shifts toward the temporal (verbal and object information processing) or parietal (spatial information processing) areas and later to the hippocampal and parahippocampal areas (memory storage and retrieval) (Brewer et al. 1998; Schacter and Wagner 1999; Schon et al. 2004). The memory tasks used in the present study might be more reliable for detecting alterations in adolescents' memory functions given that its execution involves more areas prone to high RF-EMF exposure from a mobile phone at the ear. This may partly contribute to the ambiguous results between our study and studies testing the working memory. However differences among populations with regard to specific exposures (or exposure patterns), differences in susceptibility, and other noncausal factors related to uncontrolled confounding or other sources of bias cannot be completely excluded.

Visual memory tasks similar to those applied in our study were also used in the Australian MoRPhEUS and ExPOSURE cohort studies in adolescents and primary school children. In line with our results, these studies found less accurate answers in the most frequent mobile phone and cordless phone callers (Abramson et al. 2009; Redmayne et al. 2013).

Although preliminary, findings from the laterality analysis might reflect separate lateralized neural pathways for verbal and figural memory. Figural and spatial memory processing are associated more with the right hemisphere of the brain, and verbal and auditory processing with the left hemisphere (Golby et al. 2001; Nagel et al. 2013). A more detailed description of the neural paths involved in the generation of new memory gives the influential model of working memory of Baddeley and Hitch (1974). The model differentiates between the visuospatial sketchpad for visual and the phonological loop for verbal information, running through the right and left temporal lobe, respectively. Evidence of a possible laterality effect in our study population might be consistent with impairment of this component step in object information memory processing.

How RF-EMF interacts with the brain is still unclear and no biophysical model exists for SAR values that do not noticeably increase the body temperature (International Commission on Non-Ionizing Radiation Protection 2010; Redmayne 2016). It may be speculated that our results are related to relatively consistently observed alterations in the electroencephalogram (EEG) during sleep in randomized crossover studies of participants exposed to mobile phone radiation prior to sleep (Loughran et al. 2012; Lustenberger et al. 2013; Regel et al. 2007; Schmid et al. 2012). Disturbed sleep negatively affects memory consolidation, in particular, in relation to abstract and complex tasks involving higher brain functions (Kopasz et al. 2010). Lustenberger et al. (2013) observed reduced overnight performance improvement in a motor sequence task after a night with RF-EMF exposure compared with the sham condition. Thus, future studies should clarify whether RF-EMF has an impact on sleep-facilitated learning processes via altered sleep brain activity.

Conclusion

We found preliminary evidence suggesting that RF-EMF may affect brain functions such as figural memory in regions that are most exposed during mobile phone use. Our findings do not provide conclusive evidence of causal effects and should be interpreted with caution until confirmed in other populations. Associations with media use parameters with low RF-EMF exposures did not provide clear or consistent support of effects of media use unrelated to RF-EMF (with the possible exception of consistent positive associations between verbal memory and data traffic duration). It is not yet clear which brain processes could be potentially affected and what biophysical mechanism may play a role. Potential long-term risk can be minimized by avoiding high brain-exposure situations as occurs when using a mobile phone with maximum power close to the ear because of, for example, bad network quality.

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