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Personal radiofrequency electromagnetic field measurements in the Netherlands: Exposure level and variability for everyday activities, times of day and types of area

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ABSTRACT

Knowledge of the exposure to radiofrequency electromagnetic fields is necessary for epidemiological studies on possible health effects. The main goal of this study is to determine the exposure level and spatial and temporal variances during 39 everyday activities in 12 frequency bands used in mobile telecommunication and broadcasting. Therefore, 24 h measurements were gathered from 98 volunteers living in or near Amsterdam and Purmerend, The Netherlands. They carried an activity diary to be kept to the minute, a GPS logger sampling at an interval of 1 s, and an EME Spy exposimeter with a detection limit of 0.0066 mW/m^2 sampling at an interval of 10 s in 12 frequency bands. The mean exposure over 24 h, excluding own mobile phone use, was 0.180 mW/m^2. During daytime exposure was about the same, but during night it was about half, and in the evening it was about twice as high. The main contribution to environmental exposure (calling by participant not included) is from calling with mobile phones (37.5%), from cordless DECT phones and their docking stations (31.7%), and from the base stations (12.7%). The exposure to mobile phone base stations increases with the percentage of urban ground use, which is an indication for high people density. In agreement, the highest mean exposure relates to the activities with high people density, such as travelling by public transport, visiting social events, pubs or shopping malls. Exposure at home depends mainly on exposure from people calling in the neighbourhood of the participant and thus on the number of persons in a household. In addition just the possession of DECT docking stations leads to exposure as most models transmit continuously in stand-by. Also wireless internet routers continuously transmit in the WiFi band. Though the highest exposure peaks in the WiFi band, up to 0.265 W/m^2, come from stray radiation of microwave ovens. The mean total exposure largely depends on phone calls of a high exposure level and short duration. These calls lead to potentially high contrasts as well in exposure levels between sessions of the same activity as between persons, thus posing a challenge for personal exposure prediction.

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1. Introduction

As the use of wireless telecommunication applications increases over the years, so does the use of different frequency bands. In the Netherlands the use of smartphones has increased from 30% to 40% in one year. This increased use leads not only to an increased diversity in the frequency bands of exposure to radiofrequency (RF) electromagnetic fields (EMF), but also to an increased intensity of mean total exposure over a day. For instance in Austria from 2006 to 2009 the 5% trimmed arithmetic mean exposure to UMTS increased by a factor of 13.8 and for wireless internet by a factor 9.9 (Tomitsch and Dechant, 2011). With increasing use of telecommunication and thus awareness of exposure, also the concern for possible adverse health effects grows (Infas, 2007; TNS Opinion and Social, 2011).

To investigate whether an association exists between exposure to ambient RF-EMF and adverse health effects, epidemiological studies have been conducted in several countries (Baliatsas et al., 2012). They have employed several methods with different levels of accuracy to determine or estimate the individual exposure. Some of them use spot measurements at a location where one spends most of the time, e.g. the bedroom, or the distance to fixed transmitters as a proxy for exposure. However, they are neither a good indicator for the mean exposure to environmental fields over the day, nor for exposure due to one's own calling pattern (Frei et al., 2010). Therefore, to get a better indication of environmental exposure to EMF during daily life a team of epidemiologists recommended the use of personal exposure measurements (Neubauer et al., 2007). The past five years personal exposure meters, exposimeters, have been applied in a number of European studies (Berg-Beckhoff et al., 2009; Frei et al., 2009a, b, 2010; Joseph et al, 2008; Radon et al., 2006; Thomas et al., 2008; Thuróczy et al., 2008; Viel et al., 2009a,b, 2011). Although these

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studies give a good indication of the main contributors to daily exposure, they pointed to different activities as the highest exposure activity. Moreover, exposure during activities differed highly in frequency content between countries (Joseph et al., 2010). This can be partly explained by the use of different protocols in wearing the exposimeters, and by the use of different types of exposimeters. In addition, variation exist between countries such as geographical features and policy choices that influence the type of frequencies and the transmitter locations. Furtermore, these studies investigated spatial variations based on residential features, but as their participants did not wear a GPS logger, no location specific information, e.g. the type of area, could be attached to the measurements. Therefore, spatial variability during travelling and other activities involving motion could not be determined.

The goal of this study is to facilitate and improve on the exposure assessment in future epidemiological studies. The three major aims are firstly to assess the exposure level of the Dutch population and the possible contrasts for different demographic features; secondly the variability between and within 39 everyday activities; and thirdly to study the variability with time of day and with GPS based location, especially for activities involving motion. Especially the latter aspect has not been addressed in other major exposure studies and could improve the exposure prediction models in epidemiological studies.

2. Materials and methods

We aimed to collect 24 hours' personal radiofrequency electromagnetic measurements, GPS location data and activity diary data from 100 study participants selected for diversity in personal features.

2.1. Study population

This study is to be regarded as a microenvironmental study with everyday activity as the unit of observation. To measure the exposure distribution per activity, each activity needs to be covered a representative number of times. Behaviour, activities an individual takes part in, is known to depend on personal features such as sex, age, social economic status (SES), employment and residential area (Röösli et al., 2010; Statistics Netherlands, 2010). So, to get an optimal coverage of the complete list of activities, we selected the study participants on diversity, i.e. balanced over aforementioned personal features.

In September 2009, the selection started in two steps from the TNS-Nipo internet panel (Bureau Veldkamp, Amsterdam, The Netherlands). At first, we selected a group of 3000 out of 140,000 panel members, living in the northwest of the Netherlands in the region from Purmerend to Amsterdam. By email we asked for their preparedness to carry a measurement set for 24 h and to fill out a questionnaire for a reward of 50 Euro. This resulted in a positive response of 909 persons. Subsequently, out of these 909 we selected a personal feature balanced group of 140 persons to reach at least 100 complete and faultless datasets. The surplus of 40 was necessary for mainly three reasons. Firstly, slow decay of the exposimeters due to bumping and aging may lead to faulty measurements, such as permanent registrations above, or at the detection limit, measurements with a constant jitter between two values, out-of-band response for non-neighbouring frequencybands. Secondly, inappropriate usage and diary keeping may lead to incomplete or erroneous datasets (Frei et al., 2009a; Viel et al., 2009a). Thirdly, we expected fall out of participants at the last minute. In total 21 measurements were replaced due to gradually decay of 3 out of 10 exposimeters. In later analyses 2 measurement were declined due to incorrect diary keeping, resulting in 98 complete measurements to be used in the results.

Before the measurements started all 140 selected persons returned a filled out questionnaire consisting of three parts: 1) personal characteristics, 2) residential and workplace features, 3) usage and possession of phones, wireless devices, and household equipment. The third part is necessary, since we expected indoor exposure to highly depend on these.

2.2. Exposure assessment

The measurement set consisted of an EME Spy 121 (Satimo, Cortaboeuf, France, http://www.satimo.fr) measuring the RF electric field in 12 frequency bands (88 MHz – 2400 MHz) for communication, a GPS logger of type Adapt AD-850 (Adapt, London, United Kingdom, http://www.adapt-mobile.com/), a digital watch, and a time-activity diary.

The measurement set had to be worn during all activities and in the same position on the body. In this way differences due to the directional sensitivity of the exposimeters and the shielding of the body were minimized and thus the measurements are better comparable between people and activities (Bolte et al., 2011; Mann et al., 2005; Radon et al., 2006). The EME Spy was carried in a camera bag strapped over the left shoulder and clipped on the right hip to the belt, its long axis vertically parallel to the body axis. As the exposimeter is not isotropical in its response, especially for different elevation arrival angles (Bolte et al, 2011), a tight fitting camerabag is necessary to ensure a steady position on the body. The GPS logger is carried on the left shoulder, hooked to the strap of the camera bag. Since traffic is at the right side of the road, wearing the GPS on the left side, directed towards the open road, diminishes the shadowing of the satellites. During sleep the measurement set was to be positioned on a low table next to the head. Other exemptions were if the safety of the participant or the measurement set could not be assured, e.g. during certain industrial work, sports, and wet activities such as personal hygiene or swimming.

The EME Spy 121 measures in 12 frequency bands used for communication: FM radio (88–108 MHz), TV3 (174–233 MHz), TETRA (380–400 MHz), TV4&5 (470–830 MHz), GSM uplink (880–915 MHz), GSM downlink (925–960 MHz), DCS uplink (1710–1785 MHz), DCS downlink (1805–1880 MHz), DECT (1880–1900 MHz), UMTS uplink (1920–1980 MHz), UMTS downlink (2110–2170 MHz), WiFi (2400–2500 MHz). TV3 and TV4&5 were originally the bands for analog TV broadcasts. However, in the Netherlands all broadcasts are Digital Video Broadcasting Terrestrial (DVB-T) in the TV4&5 frequency band. Also part of the radio broadcasts are Terrestrial Digital Audio Broadcasting (T-DAB) at 174–230 MHz in the TV3 band. TETRA is the protocol used for emergency services (police, firebrigade, and ambulances). GSM (also called GSM900), DCS (also called GSM1800) and UMTS are the frequency bands for mobile phone communications. Downlink stands for transmission from the base station to the cell phone, uplink for transmission from the cell phone to the base station. The DECT band is used by cordless landline phones and babyphones. WiFi is the protocol for wireless internet, but microwave ovens also operate in this frequency band. To reach at least 24 h of measurements, the sampling frequency was set at every 10th second. The maximum memory capacity is 12544 samples, leading to a dataset of approximately 35 h. The upper detection limit is 0.265 W/m^2 (10 V/m), the lower is 0.0066 mW/m^2 (0.05 V/m).

The GPS logger measured every second for a period of 20 h until the battery depleted. In this way the battery would only deplete at night when participants were asleep at home.

In the time-activity diary facing pages showed all 39 activities in columns. At the start of each new activity on a new line in the diary, the time as displayed on the digital watch is written in HH:MM:SS and a cross was set in the column of the activity. Further, on notes pages the participants were explicitly instructed to write down the use of a cordless or cell phone and all unexpected or remarkable events, a.o. the explanation for not being able to classify an activity in one of the predefined ones, or the reason and time interval not being able to wear the measurement set. The list of activities was taken from Statistics Netherlands (2010), and split into subactivities if differences were expected between frequency bands for certain activities.

2.3. Data cleaning and processing

Within 48 hours (a weekend) after the last measurement, we checked the data for unreliable measurements, such as clipping at a constant value. Even though the RF exposimeter had been calibrated by the manufacturer, the Radio Communications Agency of the Netherlands again performed an initial and end calibration in a Gigahertz Transverse Electromagnetic (GTEM) cell. Per exposimeter a different set of frequency calibration correction factors was applied as well as a correction factor for the drift over time (Bolte et al., 2011). Typically the multiplicative factors for the electric field ranged from 0.82 to 0.9 for the FM band and from 1.39 to 1.71 for the DCS downlink band. Apart from an exposimeter-dependent and time-dependent calibration factor, we also applied filters for out-of-band responses, especially for suppressing the registration of DECT signals simultaneously with a DCS downlink signal during outdoor activities (Bolte et al., 2011; Lauer et al., 2012).

2.4. Statistical analysis

The Activity Exposure Matrix contains the time weighted average power density for all 39 activities over 12 frequency bands. The total exposure is the sum of the power densities over the 12 frequency bands. Group means were calculated by pooling all available measurements on a group, f.i. all measurements classified as "walking". The robust regression on order statistics (ROS) was applied to correct for left censored measurements, assuming a log-normal distribution of the exposure (Helsel and Cohn, 1988). The minimum proportion of measurements required above the detection limit for applying ROS was 0.1% (Röösli et al., 2008). ROS fits a linear regression on the logarithms of the data versus their normal quantiles on the data above the detection limits. The regression parameters are then used to predict the "true" values of the non-measurable exposure below the detection limit. The combined set of both, predicted and measured values was used to perform calculations.

Further, to investigate the distribution over sessions of the same activity, e.g. a bike ride, we calculated the mean exposure per session. Contrasts between sessions were defined as the maximum divided by the minimum exposure. Distribution of exposure over personal features was calculated from the mean total exposure per individual. Also a trimmed mean, leaving the 10% lowest and highest values out, was calculated. Temporal analyses were made on the mean total exposure versus time of day. Spatial analyses were performed on the exposure during travelling activities in the mobile phone downlink bands versus percentage of urban ground use in four bins. Urban ground use is the percentage of the total area not in use by agriculture or nature. The percentage of urban ground use was determined by combining the GPS location information with the information per region at neighbourhood level from Statistics Netherlands (2010). As travelling activities have the broadest coverage in number of instances and geographical locations, they were assumed to be representative.

All data were analysed using R software, version 2.13.0, the robust ROS method is part of the NADA package.

3. Results

3.1. Individual exposure characteristics

Table 1 shows the distribution of the individual total exposure over the personal characteristics. The mean age of the 98 participants, 48 men and 50 women, was 44.8 years (range: 19–81, standard deviation: 16.4).

The mean total power density over the participants was 0.180 mW/m^2 (0.260 V/m), the geometric mean was 0.099 mW/m^2 (0.193 V/m). Including own calling, the mean total power density was 0.204 mW/m^2 (0.277 V/m). The DECT band contributed most (31.7%), though the total of the uplink bands was higher (total 37.5%, from GSM: 18.2%; DCS: 18.6%; UMTS: 0.7%). The WiFi band contributed 14.1%, consisting of 11.5% due to wireless internet and 2.6% due to using a microwave oven. The downlink bands contributed 12.7% (GSM: 3.8%; DCS: 7.5%; UMTS: 0.9%), FM radio 3.0%, T-DAB (TV3): 0.7%, DVB-T (TV4&5): 0.6% and TETRA: 0.1% (data not shown in tables).

Further, it was observed that due to the small number of persons per group, outliers highly influenced the mean of the time weighted averages. The contrast ratios dropped most for "at home," mean from 0.172 to 0.099 mW/m^2, and "aged 45–54", mean from 0.228 to 0.114 mW/m^2." (Table 1). From further analysis of the personal recodings outliers especially occurred in the FM (0.219 mW/m^2) and DCS downlink (0.160 and 0.256 mW/m^2) bands during sleep. In the GSM and DCS uplink bands and the DECT band due to conversations in the neighbourhood for resp. 10, 10 and 5, (0.1–1.5 mW/m^2) participants. No outliers were noticed in the TETRA and UMTS bands. The mean exposure in the WiFi band was dominated by cooking with a microwave oven by 4 participants leading to 8 minutes peaks up to the upper detection limit of 265 mW/m^2 (10 V/m).

At a worked day the mean total exposure was about 50% higher than at a non-worked day (Table 1). Mean exposure increases with SES. The age group 25–34 years has the highest mean exposure (0.239 mW/m^2). Contrasts in powerdensity (max/min) before trimming

Table 1
Distribution of individual mean total power density (mW/m^2) per personal characteristic.

	N	Mean	Contrast	Trimmed mean[a]	Trimmed contrast[a]	0%	10%	25%	50%	75%	90%	95%	99%	100%
Total	98	0.180	158	0.120	12	0.015	0.033	0.052	0.099	0.155	0.410	0.495	1.123	2.367
At home	98	0.172	933	0.091	21	0.005	0.016	0.038	0.074	0.130	0.338	0.502	1.035	4.517
Non-worked day	59	0.135	52	0.104	12	0.017	0.029	0.048	0.087	0.151	0.329	0.469	0.664	0.905
Worked day	39	0.247	158	0.155	12	0.015	0.042	0.072	0.119	0.248	0.495	1.015	1.879	2.367
SES														
Low	15	0.105	15	0.095	4	0.021	0.043	0.051	0.088	0.132	0.165	0.213	0.292	0.311
Middle	57	0.150	67	0.108	9	0.015	0.032	0.053	0.090	0.143	0.289	0.491	0.950	1.007
High	26	0.288	131	0.181	14	0.018	0.034	0.063	0.113	0.342	0.490	0.940	2.046	2.367
Age														
(18,24]	13	0.174	40	0.121	5	0.023	0.053	0.063	0.105	0.134	0.266	0.525	0.829	0.905
(24,34]	20	0.239	29	0.196	12	0.037	0.041	0.052	0.098	0.408	0.491	0.522	0.972	1.084
(34,44]	16	0.157	67	0.106	8	0.015	0.028	0.047	0.109	0.144	0.217	0.422	0.890	1.007
(44,54]	19	0.228	131	0.114	10	0.018	0.032	0.044	0.082	0.127	0.302	0.694	2.032	2.367
(54,64]	17	0.146	23	0.133	8	0.021	0.038	0.065	0.113	0.155	0.299	0.344	0.447	0.472
(64,82]	13	0.096	11	0.095	4	0.017	0.047	0.053	0.084	0.137	0.168	0.177	0.184	0.186

[a] trimmed: fraction of 0.1 left out from both end points.

range from 11 to 953, after from 4 to 21. The largest contrasts were found for the exposure distribution at home.

3.2. Time weighted average per time of day

The mean total exposure and the percentage above the detection limit during different times of the day: night (23:00–7:00), daytime (7:00–18:00) and evening (18:00–23:00) is respectively: 0.095, 0.382 and 0.183 mW/m^2 and 55, 60, 59%. Over the entire day it was 0.180 mW/m^2 and 58%. Fig. 1 shows the contributions of the frequency bands. During daytime, the main contributors to the mean exposure are DECT (0.036 mW/m^2, 28.1%) and the GSM (0.070 mW/m^2, 3.2%) and DCS (0.032 mW/m^2, 1.4%) uplink bands. The main contributor to the samples above the detection limit is GSM downlink (0.007 mW/m^2, 16.0%). In the evening the main contributor is DECT (0.162 mW/m^2, 38.6%). Over night the main contributors are DCS uplink (0.029 mW/m^2, 0.3%), WiFi (0.020 mW/m^2, 3.9%) and DECT (0.018 mW/m^2, 29.7%).

3.3. Activity exposure matrix: time weighted average between and within activities

Table 2 displays the Activity Exposure Matrix and gives for each frequency band the time weighted average calculated as the mean ROS power density per activity. The exposure in the uplink bands is displayed excluding personal phone use. All comparisons across categories were statistically significant.

Passing time at a railway station was the highest exposure activity in the FM, TETRA, TV4&5 and the GSM and UMTS downlink bands. Further highest exposure activities per frequency band are shopping at an outdoor market in the TV3, travelling by car in the GSM uplink, visiting a pub in the DCS uplink, maintenance around the house and waiting at the railway station in the DCS downlink, sleeping in the UMTS uplink, watching TV in the DECT and cooking in the WiFi band.

At home, for most activities DECT gave the highest contribution (0.069 mW/m^2, 43.4%). For cooking, eating and sleeping the main contributor was WiFi and for clearing up and personal care it was the DCS uplink.

Elsewhere inside activities were mainly dominated by the GSM and DCS uplink bands as largest contributors (0.032 mW/m^2, 19.6%; 0.064 mW/m^2, 39.3%). For attending courses and for visiting church or museum the downlink bands were the main contributors. For shopping in supermarkets and in large stores and malls the uplink bands were the highest contributors, for shopping in small shops the DECT band was the largest contributor.

Outdoor, i.e. outside a building or metal casing acting as a semi-Faraday's cage like trains, for most activities the GSM and DCS uplink bands were the highest contributors (0.077 mW/m^2, 37.0%; 0.024 mW/m^2, 11.5%). For activities near the home the main contributor was either DECT or sometimes in the beam of a base station antenna, the downlink bands. For sitting at the terrace and working outside, the uplink bands gave the highest contrubutions. For activities involving motion, the uplink bands were the highest contributors for walking and for shopping at the market, but for biking these were the downlink bands. In general the exposure to GSM base stations was half the exposure to DCS base stations.

During public transport the highest exposure was from the GSM and DCS uplink bands (0.162 mW/m^2, 56.1%; 0.048 mW/m^2, 16.6%), but driving a car led to a higher exposure in case a passenger was calling (0.314 mW/m^2, 40.5%; 0.381 mW/m^2, 49.2%). At railway stations and bus/tram stops the highest contributors were the downlink bands. Travelling by tram led to higher exposure in the downlink bands than for other means of transport.

The contrasts in mean total, excluding the uplink bands, exposure between sessions of the same activity ranged from: 2 (moped) – 650 ,722 (cooking). Contrasts were high, as during some sessions, mostly of a short duration of less than 10 min, the exposure never reached above the detection limit and the mean total exposure was set to a minimum of 6.63 10^{-5} mW/m^2 (0.005 V/m). Inclusion of uplink bands gave much higher contrast for most activities, as a few sessions of short duration with people calling with their mobile phones in the neighbourhood of the participant, led to exposures over 52 mW/m^2. Also for fixed transmitters the spread in means of sessions of the same activities was wide, like Fig. 2 shows for travelling activities in the downlink bands.

3.4. Spatial variability

In Fig. 3 the yellow profile shows the spatial exposure pattern to GSM base stations as measured during transport in train, tram and bus around Amsterdam. Moving from the city centre to the rural area the exposure decreased from permanently over the detection limit, to about 25% of the time over the detection limit in the outskirts. In rural areas the exposure was only above the detection limit when passing through the main beam of a base station antenna. Also other means of transport, train, car, and walking, showed similar patterns of decreasing exposure to base stations with decreasing percentage of urban ground use (Fig. 4). As buildings and sometimes trains and cars themselves shield the GPS logger from the sattelites, for only 78% of the samples the location could be retrieved., Additionally, we used only data from Statistics Netherlands over 2009 which were complete and up to date, in total leading to a retrieval of the percentage of urban ground use for 52% of the samples. Exposure was correlated with the percentage of samples above the detection limit, except for the 25%–50% bin for driving a car. For the GSM and DCS downlink bands with increasing urban ground use, the exposure increased for walking, but for driving a car only DCS showed this pattern. Travelling by train did not show a linear increase with urban ground use, but for all three bands showed highest exposure in the 25–50% bin. Table 2 shows that for all frequency bands increasing exposure sequence was: train-car-walk, but this sequence differed per bin of urban ground use, in the 25–50% bin this shifted to: car-walk-train.

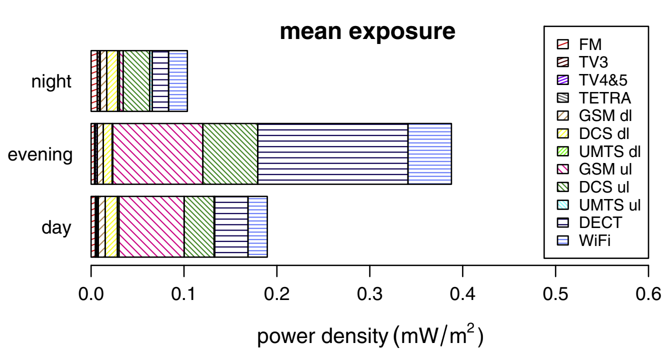

Fig. 1. Mean ROS exposure contributions per frequency band per time of day (day 7:00–18:00; evening: 18:00–23:00; night: 23:00–7:00). The exposure from downlink bands (base stations) is denoted by the 45° foreward shading, the uplink bands (cell phones) by 45° backward shading, and major indoor sources by the horizontal shading. Note that due their small contribution the exposure in the TV3, TV4&5 and TETRA cannot be distinguished from each other.

4. Discussion

This study determined for multiple daily activities the time weighted average exposure for the pooled 24-hour measurements of 98 participants in Amsterdam and Purmerend, the Netherlands. In this way we could study which activities and which frequency bands contribute most to daily exposure. After subtraction of own mobile phone use we found a pooled time weighted average overall exposure of 0.180 mW/m^2. The exposures during day, evening and night were respectively 0.183, 0.382 and 0.095 mW/m^2. Largest contributor is the DECT band, however the combined exposure from the

Table 2
Activity Exposure Matrix of ROS mean power density (mW/m[a]) in 12 frequency bands for 39 daily activities (italic: highest exposure activity for this frequency band, bold: highest contributing frequency band for this activity).

Activity	samples	sessions[b]	FM	TV3[a]	TETRA	TV4&5[c]	GSM ul[d]	GSM dl[d]	DCS ul[d]	DCS dl[d]	DECT	UMTS ul[d]	UMTS dl[d]	WIFI	TOTAL	Contrast w/o ul[e]
At home	571,394	1865	0.005	0.001	0.001	0.001	0.011	0.006	0.021	0.009	**0.069**	0.001	0.001	0.033	0.159	20664
Sleeping	258,461	106	0.006	0.003	0.000	0.001	0.002	0.007	0.022	0.013	0.018	*0.003*	0.002	**0.030**	0.108	44388
Eating at home	20,815	154	0.007	0.001	0.000	0.004	0.017	0.004	0.028	0.007	0.037	0.000	0.001	**0.043**	0.148	303408
Watch TV DVD VIDEO	84,636	220	0.004	0.002	0.000	0.001	0.021	0.005	0.003	0.004	***0.253***	0.000	0.000	0.007	0.300	18768
(game) computer or game console	68,184	279	0.008	0.001	0.003	0.001	0.011	0.004	0.008	0.007	**0.050**	0.000	0.001	0.013	0.107	41244
Doing nothing/sit still/read	40,748	231	0.003	0.000	0.000	0.001	0.009	0.005	0.018	0.008	**0.140**	0.000	0.000	0.019	0.204	2136
Receive visitors/visit	15,473	46	0.002	0.001	0.000	0.004	0.015	0.003	**0.028**	0.000	**0.028**	0.000	0.001	0.012	0.094	650772
Cook (prepare food with applainces)	21,887	160	0.002	0.000	0.000	0.002	0.020	0.003	0.022	0.004	0.032	0.000	0.000	***0.329***	0.415	1740
Vacuum cleaning	1313	17	0.003	0.000	0.000	0.004	0.000	0.006	0.000	0.013	**0.022**	0.000	0.000	0.002	0.051	1560
Wash–iron–sew (clothes)	3830	42	0.001	0.000	0.000	0.000	0.001	0.003	0.000	0.005	**0.021**	0.000	0.001	0.003	0.035	33768
Clearing up/walk around/rummaging	36,861	397	0.002	0.000	0.002	0.003	0.050	0.005	0.070	0.011	**0.055**	0.000	0.001	0.012	0.210	5340
Repairs/work shop/hobby builts	4483	28	0.006	0.000	0.000	0.004	0.012	0.003	0.005	0.004	**0.037**	0.000	0.000	0.003	0.074	8916
Personal care (wash, dress, eat)	14,703	185	0.011	0.001	0.000	0.002	0.019	0.005	**0.042**	0.011	0.016	0.000	0.002	0.007	0.116	20664
Shopping	10,288	84	0.001	0.000	0.000	0.001	**0.106**	0.006	0.012	0.012	0.028	0.000	0.003	0.003	0.172	NA
Shop-daily/supermarket	2687	25	0.002	0.000	0.000	0.000	**0.056**	0.002	0.003	0.008	0.016	0.000	0.001	0.003	0.092	2508
Shop-mall/large store	4793	24	0.001	0.000	0.000	0.001	**0.172**	0.006	0.012	0.010	0.014	0.000	0.003	0.003	0.224	1776
Shop — in shops at open street	2808	35	0.000	0.000	0.000	0.001	0.040	0.013	0.021	0.020	**0.062**	0.000	0.004	0.002	0.162	5136
Elsewhere inside	19,128	52	0.005	0.000	0.000	0.003	0.032	0.015	**0.064**	0.036	0.004	0.000	0.002	0.001	0.163	NA
Visit theater, cinema, restaurant	2806	6	0.000	0.002	0.000	0.000	**0.048**	0.004	0.010	0.004	0.002	0.001	0.001	0.002	0.074	144
Visit pub, café, disco, snackbar	1734	4	0.000	0.000	0.000	0.000	0.023	0.004	***0.491***	0.004	0.002	0.000	0.001	0.000	0.526	852
Attend education, courses	6972	18	0.010	0.000	0.000	0.007	0.048	0.013	0.034	**0.068**	0.003	0.000	0.003	0.001	0.187	6936
Appointment hairdresser, MD, etc.	2479	13	0.000	0.003	0.000	0.002	**0.026**	0.004	0.022	0.006	0.018	0.001	0.000	0.002	0.086	1572
Concerts, sports matches, conferences	1559	4	0.000	0.000	0.000	0.000	0.020	0.001	**0.032**	0.001	0.005	0.001	0.000	0.000	0.061	216
Visit church, mosque, museum	3578	7	0.000	0.000	0.000	0.000	0.001	**0.097**	0.000	0.086	0.001	0.000	0.005	0.000	0.191	12372
Work	76,781	152	0.003	0.001	0.001	0.002	**0.096**	0.007	0.031	0.013	0.036	0.002	0.003	0.007	0.202	NA
Work white collar — office and inside	63,105	96	0.002	0.001	0.001	0.003	**0.096**	0.007	0.026	0.013	0.043	0.002	0.003	0.007	0.204	5652
Work blue collar — industry and inside	8702	17	0.010	0.002	0.000	0.017	**0.094**	0.005	0.036	0.014	0.002	0.000	0.003	0.004	0.188	2532
Work blue collar — physical and outside	2839	8	0.000	0.000	0.000	0.000	**0.132**	0.006	0.033	0.025	0.005	0.000	0.002	0.000	0.205	2664
work white collar — outside	2135	31	0.003	0.000	0.000	0.000	0.075	0.011	**0.160**	0.010	0.002	0.000	0.002	0.004	0.268	852
Outdoor	24,501	352	0.012	0.003	0.001	0.002	**0.077**	0.022	0.024	0.050	0.011	0.000	0.005	0.001	0.208	NA
Relax outside (balcony/garden etc.)	1897	27	0.008	0.000	0.000	0.000	0.001	0.003	0.027	0.027	**0.101**	0.000	0.001	0.002	0.171	11400
Garden tasks	267	5	0.000	0.000	0.000	0.000	0.000	0.007	0.000	0.000	**0.025**	0.000	0.000	0.000	0.034	1092
Maintenance/repairs/hobby builts	646	9	0.000	0.000	0.000	0.001	0.000	0.087	0.000	***0.257***	0.006	0.000	*0.018*	0.000	0.370	12552
Relaxing outdoor (excl transport)	956	11	0.002	0.009	0.003	0.000	**0.045**	0.006	0.000	0.026	0.004	0.000	0.003	0.000	0.098	11400
Shop outdoor (market)	868	7	0.004	*0.017*	0.000	0.002	0.003	0.016	0.002	**0.035**	0.006	0.000	0.005	0.001	0.091	1728
Walking[f]	13720	207	0.009	0.002	0.001	0.002	**0.123**	0.023	0.025	0.040	0.005	0.000	0.005	0.001	0.236	10404
Bike	5799	77	0.028	0.002	0.000	0.004	0.027	0.024	0.032	**0.067**	0.003	0.000	0.007	0.001	0.196	10836
Moped	117	2	0.000	0.004	0.000	0.000	0.000	0.021	0.000	**0.025**	0.000	0.000	0.000	0.000	0.052	2
Bus-metro-tram stop	231	7	0.008	0.000	0.000	0.007	0.010	0.012	0.000	**0.050**	0.000	0.000	0.004	0.000	0.091	1836
Railway stations	709	16	*0.031*	0.005	*0.006*	*0.018*	0.011	***0.134***	0.001	0.103	0.000	0.000	*0.018*	0.002	0.330	12132
Train	1589	12	0.002	0.001	0.000	0.001	**0.233**	0.010	0.092	0.007	0.001	0.002	0.003	0.000	0.354	876
Tram, metro	1726	11	0.018	0.002	0.002	0.009	**0.138**	0.026	0.026	0.074	0.001	0.000	0.006	0.003	0.304	3408
Bus/minibus	376	4	0.004	0.000	0.001	0.003	0.045	0.012	**0.106**	0.045	0.000	0.000	0.005	0.000	0.222	NA
Car/van/truck	22,152	205	0.003	0.013	0.001	0.003	*0.314*	0.013	***0.381***	0.024	0.007	0.001	0.002	0.014	0.776	16332

[a] The TV3 band is only used for digital radio: Terrestrial Digital Audio Broadcasting (T-DAB).
[b] a session is an uninterrupted time period during which the same activity was performed, e.g. a bike ride.
[c] The TV4&5 band is only used for digital television: Digital Video Broadcasting Terrestrial (DVB-T).
[d] dl: downlink, i.e. from base station to mobile phone; ul: from mobile phone to base station.
[e] w/o ul: without uplink.
[f] Walks are only recorded if they were outdoor walks.

uplink bands is larger. Both, the exposure to a signal of a single frequency and the total measured exposure never exceeded the reference values of the limits in the ICNIRP guidelines (ICNIRP, 1998).

4.1. Individual exposure

Personal characteristics displaying the highest mean exposure are: full time employment, being between 25 and 34 years of age, and having a high SES. Participants with these characteristics were typically more involved in high exposure activities, such as working, travelling and waiting at the station and other activities involving a high people density, such as visiting pubs.

4.2. Exposure level and variability per activity

High mean total exposures for activities are mainly caused by people calling in the direct surrounding. This typically occurs during activities with a high people density such as public transport, car rides with passengers, social events such as pub visits, shopping in a mall, but also during activities in a multi-person household (Table 2). People calling is often the main contributor to the mean total exposure, but as it does not occur during every session of a specific activity, it is also the main contributor to large contrasts. The high variability at home is mainly due to the absence or occurrence of other members of the household calling, continuously transmitting DECT docking stations and the use of a microwave. Consequently, in exposure prediction apart from a questionnaire on the daily activity pattern, a questionnaire on the number of persons in the household potentially calling and the ownership of a DECT landline and microwave oven use is necessary.

High contrasts between sessions of the same activity do not only occur during activities with high mean total exposure, also activities with sessions of a small duration, a couple of minutes, and static activities show this behaviour. Activities yielding sessions of typically short durations, such as walking and biking, will show large contrasts between sessions of the same activity as during short duration no exposure or a high exposure event, f.i. walking through the beam of a fixed

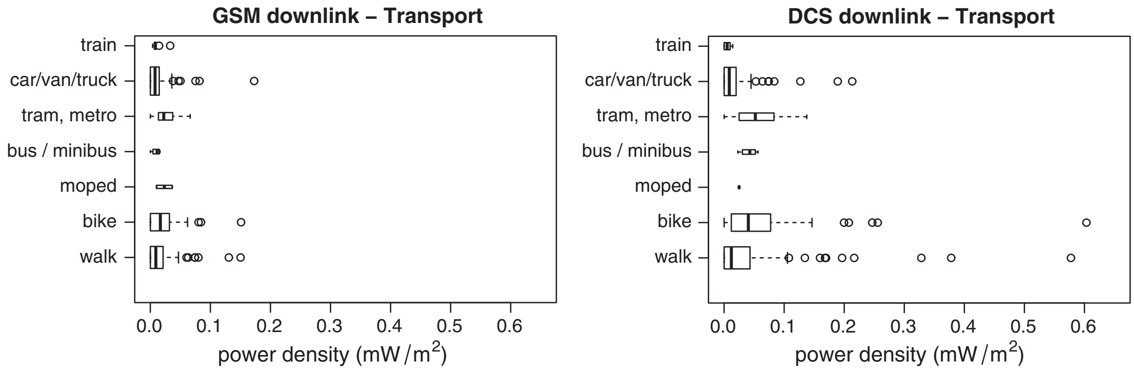

Fig. 2. Distribution of session means for the GSM downlink band (left) and DCS downlink band (right). Only sessions, i.e. uninterrupted time intervals of the same activity, e.g. a bike ride, with a duration over 5 minutes are included. The width of the boxes is proportional to the number of sessions. The whiskers reach from the 5 to 95 percentile, the hinges from the 25 to 75 percentile, the stripe denotes the median.

transmitter, may occur. In static activities, i.e. with no motion such as having dinner or watching TV, the variability within a session is very low, so the mean exposure represents the instantaneous exposure and one is either low or high exposed for the entire duration. Consequently static activities yield higher contrasts between sessions than dynamic activities in which one is alternatingly high and low exposed for the duration of the activity.

Due to the observed large exposure contrasts between sessions of the same activity, comparison between activities is difficult. As the range of mean exposure over sessions of the same activity can vary from virtually no exposure to high exposure to uplink bands because passengers are calling in a car (0.000265–52 mW/m^2), the contrast is high compared to the contrast of means over activities (0.776 / 0.051 = 15), so is the exposure contrast between persons (158). Therefore, individual exposure prediction based on an activity diary is difficult. However, partly these contrasts can be decreased by splitting activities in sub-activities according to their temporal and spatial exposure patterns.

4.3. Temporal exposure patterns

The total exposure level is highly influenced by other people calling and therefore linked to people density, which is in turn a function of location and time of day and even season of the year. The time dependent high people density areas are work and shop areas during daytime, whereas during evening and night these are the pub and residential areas. This study sample size was to small to investigate the interaction between time of day and location.

Further, though outside the scope of this research project, it is logical to assume that a seasonal variation exists. Foliage is an absorber of EMF and therefore in autumn and summer, when trees carry leaves, the transmitters have to broadcast at a higher power level compared to winter. On top of that, during winter, people will spent less time outside, and tend to walk and bike less, leading to different people densities.

In general the total mean exposure during evening is about twice the exposure during daytime (Fig. 1). In the evening the extra exposure is from calling by household members or by other people during social events elsewhere inside. Further, a major contribution is from the use of wireless internet and DECT base station in the evening. Exposure during night is still half of daytime exposure as DECT base stations and wireless internet routers will permanently transmit in stand-by at night. As exposure during the evening is about four times as high as during nighttime, people can potentially decrease their exposure themselves.

The exposure over a worked day is about 80% higher than over a non-worked day (Table 1). This is true for all frequency bands (data not shown), except WiFi, and may be explained by the exposure to

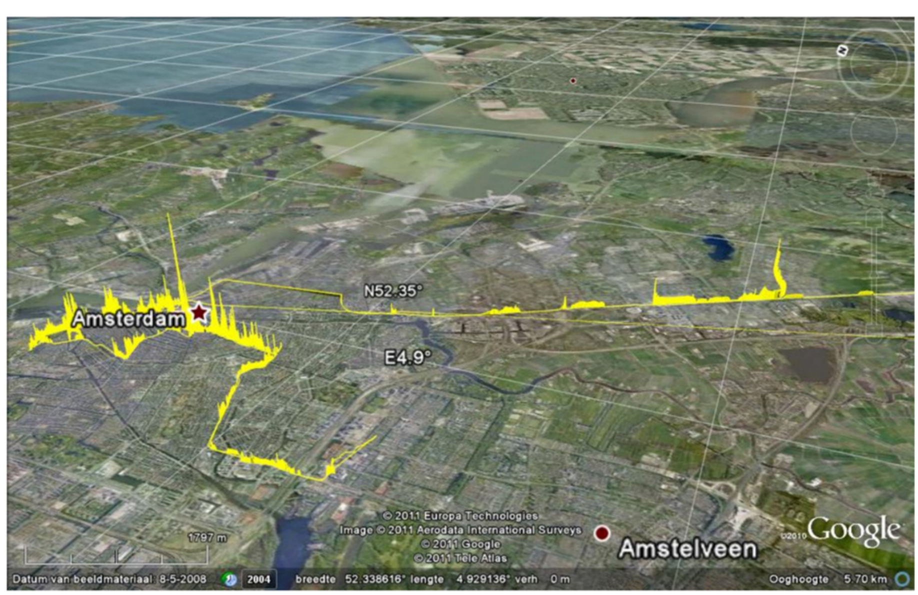

Fig. 3. Spatial pattern of exposure (yellow) to electromagnetic fields from GSM base stations during travelling by train, tram and bus. The height of the yellow profile is proportional to the electric field strength (1 km represents 1 V/m). Courtesy © 2011 Google, © 2011 Aerodata International Surveys, © 2011 Europa Technologies, © 2011 Tele Atlas. (For interpretation of the color references in this figure, ther reader is referred to the online version).

other people calling in the neighbourhood and fixed transmitters while travelling to, and being at work. WiFi exposure at work is lower than at home, as most work PC's use cables, whereas most home used internet communication devices, such as laptops, smartphones and even PC's, are wireless. Note that due to various reasons, e.g. retirement, attending school, unemployment, or part-time employment, a worked day is not the same as a workday (Monday – Friday), and a non-worked day is not per se a day during the weekend. This may partly explain why the the Swiss study (Frei et al., 2009a) found no difference between workdays and weekend days, and the French (Viel et al., 2011) only found differences less than 10%. Another explanation is the difference between countries in means of transport to work in combination with the design of the network of base stations.

4.4. Spatial exposure patterns

Spatial exposure is influenced by the coverage of the mobile telecommunication base station and other fixed transmitter networks. Downlink networks are designed to cover all locations that will be densely populated during some part of the day. Figs. 3 and 4 show that exposure diminishes from the (shopping) centre to the residential area to the rural area. As GSM and DCS base stations only can handle as many callers as timeslots available, the higher the potential people density at some part of the day, the higher the antenna and transmitter density, and therefore the denser the antenna network, the better the area is covered, leading to a permanent exposure above the detection limit in the centre. Migrating to rural areas means less antenna's so more influence of shading of the beams by buildings. Note that, since by law the telecommunication providers should cover the whole of the Netherlands exposure will be ubiquitous, but less than the detection limit of 0.0066 mW/m^2 (0.05 V/m). Increase in exposure from rural, peri-urban to urban areas (Viel et al., 2009b) and with size of the population of the city (Thomas et al., 2008) was reported earlier, but only for the area of residence and not for all outdoor measurements, as earlier studies did not use a GPS logger.

Fig. 4 shows that exposure does not increase linearly with percentage urban ground use. The exposure in a car is typically highest in the bin of 25–50% urban ground use, this is caused by the relative dense coverage of highways and the absence of reflecting buildings, leading to a relative high percentage of time above the detection level (GSM: 25%, DCS: 15%) in combination with the fact that most of the time during a ride is spent in those areas, the mean exposure is highest there. A similar explanation is valid for travelling by train, though railways are less densely covered.

Further, note that the exposure to DCS downlink is about a factor two higher than to GSM downlink bands (Table 2 and Fig. 4). This is in accordance with the median of maximum effective radiated power, which is 132.8 W for GSM and 346.7 W for DCS transmitters (Antenneregister, 2009). As we observe a trend over time to replace DCS transmitters with GSM transmitters, and a growing number of UMTS transmitters to enable mobile internet use on smart phones, we expect that exposure in the GSM and UMTS downlink bands will increase in the future.

4.5. Comparable studies

Comparable diary studies have been performed in France (Viel et al., 2009a,b, 2011) Switzerland (Frei et al., 2009a; Röösli et al., 2008), Germany (Berg-Beckhoff et al., 2009) and with the Maschek exposimeter in Germany (Radon et al, 2006; Thomas et al., 2008). Also smaller studies have been performed in Austria, Belgium, Hungary, Slovenia and the UK (Joseph et al., 2008, 2010; Mann, 2010; Thuróczy et al., 2008). The major difference with other diary studies in Germany, France and Switzerland is that we included a GPS logger to determine the location of exposure. The mean total exposure and the three major contributions differ between studies (French–Swiss–Dutch): mean total: 0.107–0.130–0.180 mW/m^2; downlink bands: 22.4%–32.0%–12.7%; the uplink bands: 18.8%–29.1%–37.5%; and the DECT band: 16%–22.7%–31.7%. These differences may be partly explained by the shifting frequency content over time and the composition of the group of participants.

The difference in the mean can partly be explained by the difference in frequency contents due to the time of execution of the studies 2005–2006, 2007–2008, 2009–2010. Therefore a trend of increasing exposure with time can be observed, as also has been noted in Austria (Tomitsch and Dechant, 2011). Another part of the explanation is in the sampling interval (13–90–10 s), as the larger the interval, the lower the mean as short peaks like passing through the beam of a downlink station and passing someone calling are missed. That does explain the higher mean value in our study with respect to the Swiss, but not with respect to the French. The major source of the difference is the higher contribution of uplink bands in the Dutch study, which may be explained by a higher intensity of mobile phone use over the 5 year time difference with the French study. This may also account for the remarkable and consistently higher exposure in the downlink than the uplink bands, except for travelling by bus or train. It is of importance to see if over time with increasing exposure and changing frequency contents also the occurrence of health effects increases.

The composition of the group of participants is another probable cause for the difference in the total mean. We selected the 98 participants for equal group sizes over a number of personal features (sex, age, SES, etc.), thus selecting a group not representative for the entire Dutch population. This led to an overrepresentation, about 30% compared to the entire Dutch population, of the group of younger people (18–34 years) who tend to work, travel and go out more than older people and therefore spent more time in activities with a high people density, leading to a higher exposure. Older people (35–44; 65–82 years) were underrepresented by about 25%. The mean total exposure for our sample will therefore be slightly higher, up to 4%, than for the Dutch population. The French group of 377 people was randomly selected but only in two cities, and the Swiss group of 166 people was partly random and partly 17 people living near base stations, accounting for their relatively high percentage of the downlink bands to the total.

4.6. Considerations for future research

As long as no specific exposure response model is studied also associations between other exposure metrics than time weighted average exposure, e.g. number of peaks above a threshold and the irregularity of the signal on the scale of minutes or the modulation, should be further explored.

Röösli et al. (2010) proposed improvements for future microenvironmental surveys. On top of those, we found the need for improved exposimeters, the use of an optimal sampling interval, number of sessions per activity and duration of activities and surveys. As we suspect time trends in exposure, repeatability of measurements should also be further investigated.

The limitations of the exposimeter measurements have been discussed in several papers (Bolte et al., 2011; Lauer et al., 2012) and involve correction factors, residual uncertainties due to calibration, multiple frequencies, signal modulation, angle of arrival and body shielding, but most of all the limited number of frequency bands which leaves the exposure to parts of the spectrum uncovered. In general, these measurements tend to underestimate the actual exposure. Therefore, a maximum frequency-dependent correction factor of 1.1–1.6 should be applied to the electric field to correct for predictable systematic errors (Bolte et al., 2011).

Furthermore, for the GSM and DCS uplink bands the EME Spy registers the maximum burst over a measurement interval, and as a single cell phone only transmits one out of every eight time slots, in theory the overestimation can be a factor 8 if no other phone is transmitting. In the GSM and DCS downlink bands the EME Spy registers the minimum exposure value during a measurement interval thus mainly measuring the continuously transmitting BCCH channel and not all ether traffic due to cell phones communicating, leading to an underestimation of the true exposure. During daytime, when multiple phones are contacting a base station simultaneously, the exposure is probably underestimated and the true exposure could be higher. As in practice the number of slots used is unknown, similar to the other European studies, this is part of the uncertainty and no correction has been performed. In future surveys the use of a new exposimeter with a true RMS detector instead of the currently used logarithmic one is preferable.

As not all activities were covered with an equal amount of samples or sessions, the means have different reliability. Further, the difference in duration between sessions of the same activity could lead to a higher variability, and thus a less well defined mean. Other important factors for variability are time of day, percentage of urban ground use and residential features. Therefore, in future research there is a need for a larger dataset covering more different microenvironments per activity, by more people, as this would give the opportunity for further investigation and quantification of these effects by regression modeling. In addition this requires the development of a multilevel method capable of handling robust ROS (Röösli et al., 2010). Further, as long as no specific exposure response model is studied also associations between other exposure metrics than time weighted average exposure, e.g. number of peaks above a threshold and the irregularity of the signal on the scale of minutes or the modulation, should be further explored.

The repeatability of measurements is yet unknown. Even though Frei et al. (2009a,b) showed that the spearman coefficient between repeated measurements with the same participants is over 0.7, this may not be true for other repeated sessions of activities elsewhere at the same microenvironment at the same time of day, e.g. a bike ride from home to work between 8:00 and 8:30. If these exposures change systematically within the interval of weeks then a time dependent correction factor could be applied, else if the changes are random they may lead to uncertainties in the prediction of exposure. Also the influence for time of day, by repeating the activity in the same microenvironment at another time of day should be investigated to be able to make corrections between day and evening.

Finally, the introduction of new communication technologies will lead on the one hand to new exposure contribution in new frequency bands, but on the other hand they will lead to diminished use of older technologies in existing bands (Tomitsch and Dechant, 2011). Therefore, an Activity Exposure Matrix as well as a questionnaire on the use of electric equipment, especially communication devices, which are to be used in epidemiological research should be regularly updated.

5. Conclusions

The ICNIRP reference levels were never exceeded (ICNIRP, 1998). However, we found an indication for an increasing exposure trend

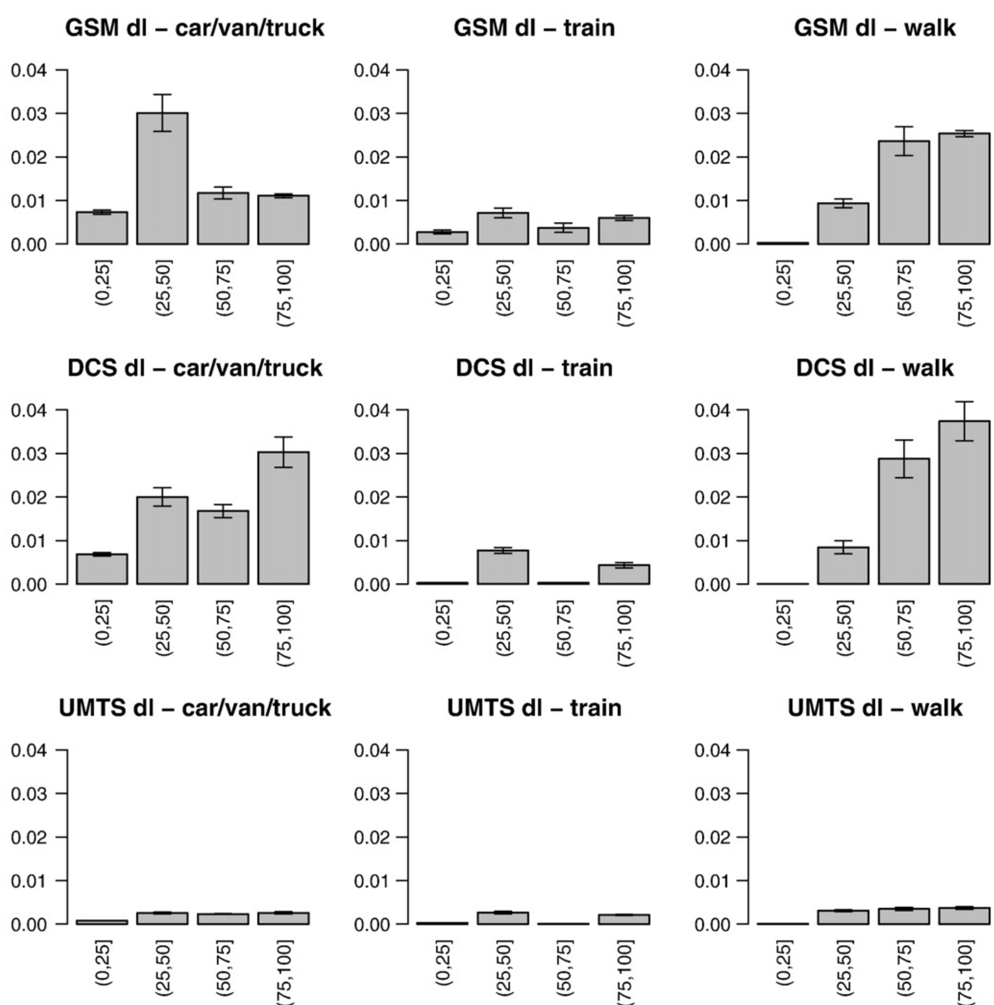

Fig. 4. Mean power density (y-axis left) and percentage above detection limit (y-axis right) per percentage of urban ground use, the percentage of the total area not in use by agriculture or nature, for GSM (upper), DCS (middle), and UMTS (lower) downlink bands. Error bars depict standard error of ROS mean.

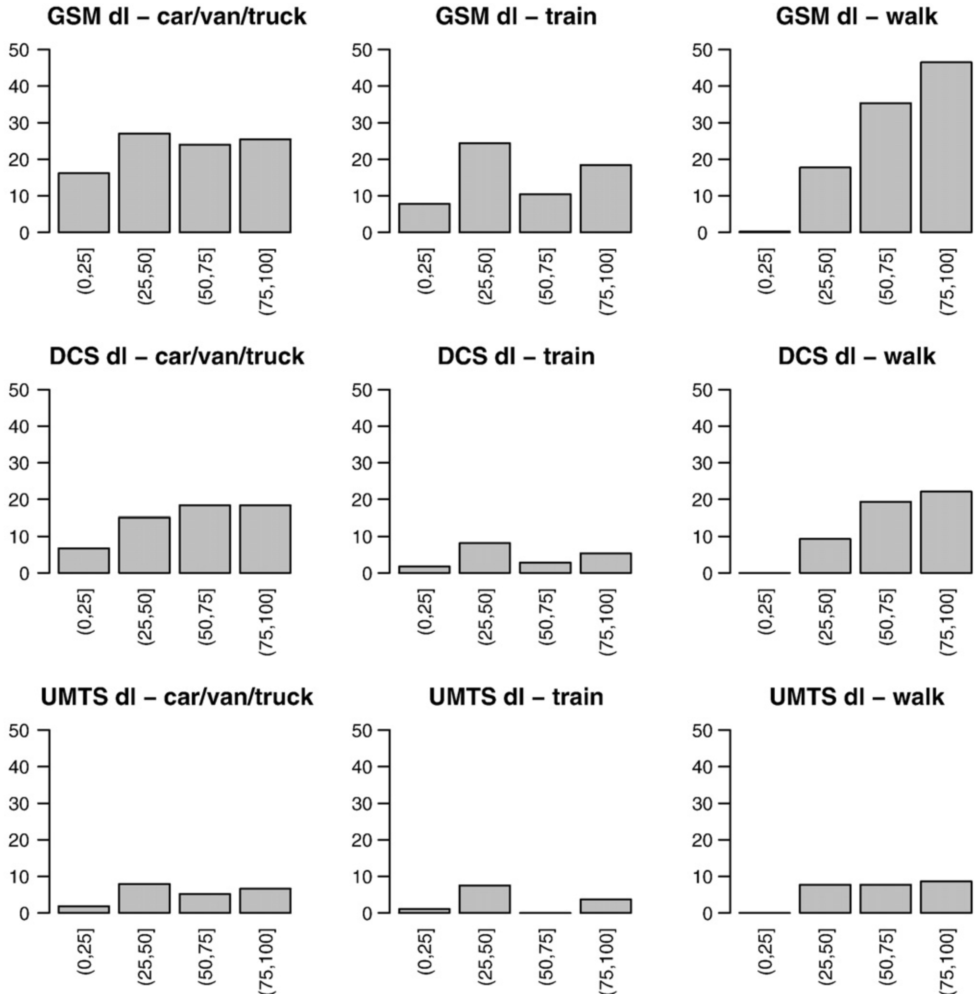

Fig. 4 (*continued*).

with time by comparing our results with the earlier French and Swiss studies. Therefore, it is of importance to repeat this kind of study over time to investigate whether also the occurrence of health effects increases, especially for groups of people with idiopathic environmental intolerance. Ideally, the interval should be large enough to measure differences in the use of existing or new wireless media, in our comparison 2 years, but small enough not to miss upcoming exposures.

As this survey is the first major study in which participants carry a GPS logger, the influence of the type of area on the exposure level during activities involving motion could be analysed qualitatively as well as quantitatively. By plotting the exposure levels on the map, not only areas of high exposure peaks can be pointed out, but also the correlation between differences in exposure and spatial features could be analysed. After coupling the data with a geographical database a further quantitative analysis showed that the exposure to downlink bands increases with the percentage of urban ground use, except for specific modes of transport as highways which even in rural areas are relatively densely covered with base stations. This spatial information explains part of the within variability for these activities and should be taken into consideration if they are used in a prediction model.

The exposure contrasts between different sessions, e.g. different bike rides, of the same activity are relatively high compared to the contrasts between activities. Typically high contrasts between sessions of the same activity occur in activities with a high mean total exposure, activities with sessions of a small duration, a couple of minutes, and static activities. As a result of the high contrast between sessions of the same activity also contrasts between persons are high, and exposure prediction is complex. The possibility of predicting one's exposure based on demographic features should be further explored, as it would be a more objective method than asking people to fill out a questionnaire on activities.

Nevertheless, exposure prediction or assigning people in lowly and highly exposed groups by means of questionnaires on daily activity patterns can be improved on by splitting activities in sub-activities according to their temporal and spatial exposure patterns, i.e. by the time of day and the percentage of urban ground use. In addition, questions on devices that contribute most to one's exposure: own calling and the number of persons in the household potentially calling; the ownership of a DECT phone and wireless internet router; and microwave oven use, are necessary.

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