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Outdoor and indoor sources of residential radiofrequency electromagnetic fields, personal cell phone and cordless phone use, and cognitive function in 5–6 years old children

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ABSTRACT

Background: Little is known about the exposure of young children to radiofrequency electromagnetic fields (RF-EMF) and potentially associated health effects. We assessed the relationship between residential RF-EMF exposure from mobile phone base stations, residential presence of indoor sources, personal cell phone and cordless phone use, and children's cognitive function at 5–6 years of age.

Methods: Cross-sectional study on children aged 5–6 years from the Amsterdam Born Children and their Development (ABCD) study, the Netherlands (n=2354). Residential RF-EMF exposure from mobile phone base stations was estimated with a 3D geospatial radio wave propagation model. Residential presence of indoor sources (cordless phone base stations and Wi-Fi) and children's cell phone and cordless phone use was reported by the mother. Speed of information processing, inhibitory control, cognitive flexibility, and visuomotor coordination was assessed using the Amsterdam Neuropsychological Tasks.

Results: Residential presence of RF-EMF indoor sources was associated with an improved speed of information processing. Higher residential RF-EMF exposure from mobile phone base stations and presence of indoor sources was associated with an improved inhibitory control and cognitive flexibility whereas we observed a reduced inhibitory control and cognitive flexibility with higher personal cordless phone use. Higher residential RF-EMF exposure from mobile phone base stations was associated with a reduced visuomotor coordination whereas we observed an improved visuomotor coordination with residential presence of RF-EMF indoor sources and higher personal cell phone use.

Conclusions: We found inconsistent associations between different sources of RF-EMF exposure and cognitive function in children aged 5–6 years.

Abbreviations: ABCD, Amsterdam Born Children and their Development; DASS, Depression Anxiety Stress Scale; LTE, Long Term Evolution technology; NOSI, Nijmeegse Ouderlijke Stress Index; RF-EMF, radiofrequency electromagnetic fields; Wi-Fi, Wireless Fidelity

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1. Introduction

Radiofrequency electromagnetic fields (RF-EMF) have developed into a nearly ubiquitous environmental exposure. RF-EMF exposure sources include mainly cell phone and cordless phone use, outdoor sources (i.e. mobile phone base stations and broadcasting stations), and indoor sources (i.e. cordless phone base stations and Wireless Fidelity (Wi-Fi) access points). Each exposure source leads to different patterns and levels of exposure: whereas personal cell phone and cordless phone use lead to localised exposures at the head of usually short duration, outdoor and indoor sources result in more homogeneous whole-body and longer duration exposure of considerably lower RF-EMF levels (Health Protection Agency, 2012).

Observational studies using self-reported data on cell phone use (Abramson et al., 2009; Redmayne et al., 2016; Thomas et al., 2010), cordless phone use (Redmayne et al., 2016), measured residential RF-EMF levels from mobile phone base stations (Hutter et al., 2006), or measured total spectrum RF-EMF levels in the immediate surrounds of the participant's house (Calvente et al., 2016) showed associations with certain cognitive function tests in adults and adolescents or children of 8–15 years old although results were inconsistent between studies. No previous observational studies have evaluated the association between several RF-EMF exposure sources and cognitive function in younger children. It has been suggested that children may be more vulnerable to different environmental exposures because of their developing nervous system (Rice and Barone, 2000). Due to the ubiquity of the RF-EMF exposure, even if low risks associate with RF-EMF they may translate into large public health implications.

Therefore, the aim of the present study was to assess the association between residential RF-EMF exposure from mobile phone base stations, residential presence or absence of indoor sources of RF-EMF, cell phone use, and cordless phone use, and children's cognitive function at 5–6 years of age in a large population-based cohort study.

2. Material and methods

This study was embedded in the Amsterdam Born Children and their Development (ABCD) Study (www.abcd-study.nl), a community-based prospective cohort study that examines the relationship of maternal lifestyle and psychosocial determinants during pregnancy, to multiple aspects of development and health of the child (van Eijsden et al., 2011). Between January 2003 and March 2004, 8266 pregnant women were enrolled during their first prenatal visit to an obstetric care provider. Their children were followed from birth. Children's cognitive function was assessed at 5–6 years old. When children were 7 years old a questionnaire (postal or via web) was administered to the mothers including retrospective information on RF-EMF exposure sources pertaining to the time point of the cognitive function tests. A total of 2354 children with available data on exposure and outcome variables were included (Supplementary Fig. A.1). Approval of the study was obtained from the Central Committee on Research involving Human Subjects in the Netherlands, the Medical Ethical Committees of the participating hospitals, and the Registration Committee of the Municipality of Amsterdam. The study was conducted in accordance with The Code Ethics of the World Medical Association (Declaration of Helsinki).

2.1. Residential RF-EMF exposure from mobile phone base stations

Residential RF-EMF exposure from mobile phone base stations was estimated using the 3D geospatial radio wave propagation model NISMap (Bürgi et al., 2010; Beekhuizen et al., 2013, 2014; Huss et al., 2015). In brief, NISMap computes the field strengths of mobile phone base stations for any location in 3D-space using detailed characteristics of the antennas (location, service and frequency, direction, output power, height of each antenna) and the 3D geometry of the urban environment. The 3D geometry consisted of a box model of all buildings in the Netherlands, retrieved by combining building data of the Netherlands' Mapping Agency (Kadaster) and the Netherlands' elevation model (Actueel Hoogtebestand Nederland, AHN2) from 2013. NISMap uses the box model to estimate shielding and diffraction by buildings. Since we were interested in mobile phone base station radiation, we assessed the downlink component of the three mobile phone communication bands (GSM900, GSM1800, and UMTS), using a country-wide mobile phone base station data set from 2011. At the time of the study, Long Term Evolution technology (LTE, also called 4G) was not yet implemented in the Netherlands. Home addresses where children were living at the time of the cognitive function tests were geo-coded using Dutch cadastral data. As the intensity of RF-EMF differs with height, we estimated height above ground of the room in which children spent most of their time, i.e. their bedroom. We collected information on the floor level of their bedroom and the total number of floors using questionnaires administered to the mothers and obtained the height of the building from our 3D-building data. We computed the height above ground with the following formula: Height=(BuildingHeight in m/TotalNrFloors)*BedroomFloor+1.5 m. Using NISMap and the retrieved x,y,z coordinates, we computed the RF-EMF exposure from mobile phone base stations at each home location. NISMap has been validated with outside, inside, and personal measurements and has been shown to make reliable rank-order predictions of downlink exposure (Beekhuizen et al., 2014, 2013; Martens et al., 2015). Continuous RF-EMF exposure levels were categorized as low (<50th percentile), medium (50–90th percentile), and high exposure (>90th percentile). For a subset of 478 children, we performed measurements of RF-EMF fields in the classroom where they were studying at the time point of the cognitive function tests. These measurements have been described elsewhere (Beekhuizen et al., 2014). Of the 201 classrooms where we did measurements, 6 had both a cordless phone base station and a Wi-Fi router inside or within 5 m of the classroom, 15 had only a cordless phone base stations, and 11 only a Wi-Fi router inside or within 5 m of the classroom. Reliable information on presence or absence of cordless phone base station and Wi-Fi routers was unavailable for 35 classrooms. For another subset of 349 children we had exact location information (x, y, z coordinates) on where their classroom was situated within the building. For these children we could additionally model the exposure at the classroom using NISMap. We used the best available measure of RF-EMF exposure from mobile phone base stations at the classroom that we had for the children, meaning measured exposure when we had measurements and modelled exposure for the remaining subgroup. We first accounted for the slight overestimation of our modelled (at home and at school) compared to the measured exposure (factor 1.29) (Beekhuizen et al., 2014). We then combined residential exposure by weighing it 6/7th and classroom exposure by 1/7th. This corresponds to roughly 24 h children of that age spend at school per week in the Netherlands. Combined residential and classroom RF-EMF exposure levels were categorized as low, medium, and high exposure, using the cut-off points (<50th, 50t–90th, and >90th percentile) of the residential RF-EMF exposure in order to be comparable.

2.2. Residential presence or absence of indoor sources of RF-EMF

Presence or absence of the main residential RF-EMF indoor sources (i.e. cordless phone base stations and Wi-Fi) at the time point of the cognitive function tests was asked to the mothers using questionnaires (Supplementary Table A.1). We combined the two 2 questions into a single exposure variable categorised as neither (no cordless phone base stations and no Wi-Fi), either cordless phone base stations or Wi-Fi, and both (cordless phone base stations and Wi-Fi).

2.3. Children's cell phone and cordless phone use

We asked the mother about the frequency of the child's cell phone and cordless phone use at the time point of the cognitive function tests (Supplementary Table A.1). We categorised the frequency of both phone uses into 4 categories (none, <1call/week, 1–2calls/week, ≥ 3calls/week) and into 2 categories (no use vs. use).

2.4. Children's cognitive function

Children's cognitive function measured as speed of information processing, inhibitory control, cognitive flexibility, and visuomotor coordination was assessed at 5–6 years old (2008–2010) using 4 tasks from the Amsterdam Neuropsychological Tasks program, a computerized assessment program (De Sonneville, 1999). The psychometric properties of this battery have been found satisfactory (e.g. test-retest reliability coefficient range from 0.70 to 0.85) (Koekkoek et al., 2008). Children were individually tested predominantly in the morning or early afternoon during school days in a quiet room by trained investigators. The tasks were presented on a laptop and responses to task stimuli had to be made using the mouse. Before starting each task, the investigator gave a verbal task instruction while showing the child an example of the task on the computer screen. Thereafter, the child did a practice run to become familiar with the task stimuli and response mode. When the investigator felt sure that the child understood the task demands the test trial started.

2.4.1. Speed of information processing

Speed of information processing was measured with the baseline speed task (De Sonneville et al., 2002). This task requires minimal cognitive effort, only some attention function. The child was required to respond as quickly as possible when a white fixation cross in the centre of the computer screen changed into a white square. First, responses were made through a mouse click with the non-preferred hand, and secondly, with the preferred hand. Each part consisted of 32 trials (1–2 min). Signal duration was variable until response, and a response was considered valid when made 150–4000 ms after stimulus appearance. A random inter stimulus interval was used ranging from 500 to 2500 ms. Mean reaction time (in ms) and within-subject SD of the reaction time were extracted.

2.4.2. Inhibitory control and cognitive flexibility

Inhibitory control and cognitive flexibility, two executive functions, were measured with the response organization task (De Sonneville et al., 2002). The task consisted of 3 parts in which they increase in complexity: i) Part 1, named fixed compatible: when a red ball appeared on the left side of a white fixation cross, children had to click the left mouse button with their left forefinger, and vice versa; ii) Part 2, named fixed incompatible, a more complex task: the reaction pattern was reversed, when a white ball appeared on the left side of the fixation cross, children had to click the right mouse button with the right forefinger, and vice versa; iii) Part 3, named random mix, the most complex task: random mix of part 1 and part 2. There were 30 trials per part in which signal duration is variable until the child responds. Part 1 and 2 had a duration of 3–4 min each, and part 3 a duration of 6–8 min. Children made a valid response when they click the right mouse button 200–6000 ms after the stimulus appears on the screen. The post-response interval in this task was constant, 1200 ms after a response a new stimulus appears. Mean reaction time (in ms), within-subject SD of the reaction time, and percentage of errors were extracted for each part. The difference in the 3 outcomes (i.e. mean reaction time, within-subject SD of the reaction time, and percentage of errors) between part 1 and part 2 was a measure of inhibitory control, and the difference in the 3 outcomes between part 1 and compatible part 3 a measure of cognitive flexibility.

2.4.3. Visuomotor coordination

Visuomotor coordination was assessed using the pursuit task and the tracking task (Kalff et al., 2003). The pursuit task requires concurrent planning and execution of movements. The child was required to follow as closely as possible with the mouse cursor a target that moved randomly across the computer screen at a constant speed of 10 mm/s, using first the non-preferred hand first and secondly the preferred hand. Each part had a duration of 1 min. The distance between the cursor and the moving target (in mm) was calculated automatically per second. Mean distance between the mouse cursor and the moving target (in mm) and within-subject SD of the distance were extracted.

The tracking task required less executive demands than the pursuit task. The task measured the quality of movement along a familiar and planned trajectory. The child was required to draw as quickly and accurately as possible with the mouse cursor the midline between two circles, using first the non-preferred hand and secondly the preferred hand. Each part had a duration of 1 min as maximum. The program divides the trajectory into 60 radially equal segments and computes the distance between the trajectory and an (invisible) midline per segment, resulting in 60 deviation scores. Mean distance between the trajectory and the (invisible) midline (in mm) and within-subject SD of the distance were extracted. Total time to complete the task was also extracted.

2.5. Potential confounding variables

Potential confounding variables were chosen a priori using directed acyclic graphs (Hernán et al., 2002). At enrolment, information on maternal country of birth was obtained by a questionnaire completed by the mother during pregnancy. Child's sex was obtained from child health care registries. A postal questionnaire when the children were 5–6 years old provided information on maternal characteristics at that time point including age, education (based on the years after primary school: high (≥ 10years), medium (6–9years), and low (≤ 5years)), weight and height, tobacco use, alcohol consumption, depression, anxiety, and stress, as well as parental financial situation, mother-to-child attachment, number of siblings of the child, and child daily time playing with computer or video games. Maternal body mass index was calculated (kg/m^2). Maternal depression, anxiety, and stress were assessed using the Depression Anxiety Stress Scale (DASS) (Lovibond and Lovibond, 1995). Mother-to-child attachment was measured using the attachment subscale of the parent domain of the Nijmeegse Ouderlijke Stress Index (NOSI) (De Brock et al., 1992). Higher DASS scores indicate greater levels of depression, anxiety, or stress, whereas higher mother-to-child attachment score reflects poorer attachment. Child's age at the cognitive function tests was collected. Besides individual socioeconomic position indicators (maternal education and parental financial situation) we estimated an area socioeconomic position indicator by matching children's addresses at 5–6 years old with a map of the percentage of persons with a low income (<40th percentile of the Dutch income distribution) at the neighbourhood level (CBS, 2001).

2.6. Statistical analysis

Among children with available data on exposure and outcome variables ($n = 2354$) we performed multiple imputation of missing values of potential confounding variables using chained equations where 25 completed datasets were generated and analysed using the standard combination rules for multiple imputation (Supplementary Table A.2) (Spratt et al., 2010; Sterne et al., 2009). Distributions in imputed datasets were similar to those observed ($n = 1881$) (Supplementary Table A.3).

Differences in maternal socioeconomic characteristics during pregnancy between included and non-included subjects were compared using a chi-square or Student's *t*-test. Maternal, parental, and child characteristics according to categories of the different exposure variables were described using means (standard deviation) or proportions, with chi-square or ANOVA tests applied.

We used linear regression models to assess the association between each exposure variable separately and each cognitive function measure. After assessing the linear regression assumptions, most of the cognitive function measures were transformed to normalise the skew of residuals (Supplementary Table A.5). Higher values of each cognitive function measure indicated a poorer performance of the test reflecting a reduced cognitive function. Models were first adjusted for child's age at cognitive test (minimally-adjusted models). Secondly, models were additionally adjusted for all potential confounding variables described above (fully-adjusted models). Models assessing visuomotor coordination with the tracking task were additionally adjusted for the total time to complete the task. We performed several sensitivity analyses: i) using the combined residential and classroom RF-EMF exposure from mobile phone base stations for those children with both estimations; ii) separating the presence of cordless phone base station and Wi-Fi at home using a 4 category variable categorized as neither (no cordless phone base stations and no Wi-Fi), cordless phone base stations but no Wi-Fi, Wi-Fi but no cordless phone base stations, and both (cordless phone base stations and Wi-Fi); iii) restricting the sample to those subjects with complete data on exposures, outcomes, and potential confounders ($n = 1881$); iv) additionally adjusting all models for children's attention deficit and hyperactivity symptoms reported by their primary schoolteacher when they were 5 years old using the Strength and Difficulties Questionnaire (Goodman, 1997). Statistical tests of hypotheses were two-tailed with significance set at $P < 0.05$. Statistical analyses were conducted using STATA (version 12.0; StataCorporation, College Station, TX, USA).

3. Results

Overall, mothers included in the present analysis had a higher socioeconomic position than those not included (Supplementary Table A.4). Median measured RF-EMF levels from mobile phone base stations at the classrooms was 0.004 mW/m^2 (interquartile range 0.001–0.013). Correlation between residential RF-EMF exposure from mobile phone base stations and all other sources of RF-EMF exposure was low (between -0.07 and 0.02) (Supplementary Table A.6). Correlation between personal cell phone use and personal cordless phone use was moderate (0.40).

Residential RF-EMF exposure from mobile phone base stations did not show a clear relationship with maternal, parental, or child's characteristics, whereas children with presence of residential RF-EMF indoor sources had a higher proportion of mothers from high socioeconomic position and a lower proportion of mothers with depression and anxiety symptoms compared to those children without cordless phone base stations and Wi-Fi at home (Table 1).

Around 52.0% of the children at 5–6 years old did not use the cell phone, whereas 6.4% made 1–2 calls/week and 4.1% 3 or more calls/week (Table 2). Mothers of children with higher cell phone use had a lower socioeconomic position. Regarding cordless phone use, only 15.6% of the children did not use the cordless phone, 17.6% made 1–2 calls/weeks and 9.4% 3 or more calls/week. Children with higher cordless phone use (3 or more calls per week) more often had a mother from lower socioeconomic position and with depression and anxiety symptoms compared to those with relatively lower cordless phone use (less than 1 call per week), while children who did not use a cordless phone showed a similar relationship with maternal, parental, and child's characteristics than those with a higher cordless phone use.

Children with presence of residential RF-EMF indoor sources showed an improved speed of information processing (i.e. a reduced slowness and fluctuation) compared to those children without cordless phone base stations and Wi-Fi at home (Fig. 1(A)). Children exposed to higher levels of residential RF-EMF from mobile phone base stations and with presence of residential RF-EMF indoor sources showed an improved inhibitory control and cognitive flexibility (i.e. a reduced slowness and percentage of errors, respectively) compared to those children exposed to lower levels of RF-EMF from mobile phone base stations and those children without cordless phone base stations and Wi-Fi at home, respectively (Fig. 1(B) and (C)). Higher personal cordless phone use showed a reduced inhibitory control and cognitive flexibility (i.e. an increased slowness) compared to those children with a non-use of cordless phone. Results were similar when personal cordless phone use was assessed as dichotomous variables (yes vs. no) (data not shown).

Children with presence of residential RF-EMF indoor sources showed an improved visuomotor coordination assessed with the pursuit task (i.e. a reduced inaccuracy and fluctuation) compared to those children without cordless phone base stations and Wi-Fi at home (Fig. 2(A)). Personal cell phone use showed an improved visuomotor coordination assessed with the pursuit task (i.e. a reduced inaccuracy and fluctuation) compared to those children with a non-use of cell phone. Results were similar when personal cell phone use was assessed as dichotomous variables (yes vs. no) (data not shown). Children exposed to higher levels of residential RF-EMF from mobile phone base stations showed a reduced visuomotor coordination assessed with the tracking task (i.e. an increased inaccuracy and fluctuation) compared to those children exposed to lower levels of RF-EMF from mobile phone base stations (Fig. 2(B)).

Effect estimates were similar in the minimally-adjusted models (Supplementary Figs. A.2–A.3). We observed comparable results when we assessed the association between the combined residential and classroom RF-EMF exposure levels from mobile phone base stations and all outcomes compared to the analysis of residential RF-EMF exposure levels from mobile phone base stations, as well as when we assessed the presence of cordless phone base station and Wi-Fi at home separately (data not shown). Results from the complete case analysis did not differ from the main analysis using multiple imputation data (Supplementary Figs. A.4–A.5). When all models were additionally adjusted for children's attention deficit and hyperactivity symptoms, the results remain materially unchanged (data not shown).

4. Discussion

The present study is, to our knowledge, the first to assess RF-EMF from several sources – including residential RF-EMF exposure from mobile phone base stations, presence of the main residential RF-EMF indoor sources (cordless phone base stations and Wi-Fi),

Table 1.
Maternal, paternal, and RF-EMF exposure at home from outdoor and indoor sources.

	Residential RF-EMF exposure from mobile phone base stations								**Presence of residential RF-EMF indoor sources (cordless phone base station and Wi-Fi)**							
	< 50th percentile		**50–90th percentile**		**> 90th percentile**				**Neither**		**Either cordless phone or Wi-Fi**		**Both**			
	(n = 1132)		**(n = 862)**		**(n = 234)**		***P*-diff**	***P*-trend**	**(n = 112)**		**(n = 622)**		**(n = 1607)**		***P*-diff**	***P*-trend**
Maternal characteristics																
Education							0.031	0.112							< 0.001	< 0.001
High	74.0		69.2		73.0				45.0		62.3		77.6			
Medium	18.8		19.4		18.5				26.6		24.7		16.7			
Low	7.3		11.3		8.6				28.4		13.0		5.7			
% persons with low income in neighbourghood	35.9	(9.6)	36.4	(8.7)	37.1	(8.6)	0.163	0.002	40.3	(7.7)	37.5	(8.8)	35.5	(9.2)	< 0.001	< 0.001
Country of birth (non-Dutch vs. Dutch)	16.3		23.2		21.8		< 0.001	< 0.001	45.5		24.1		16.3		< 0.001	< 0.001
Age (years)	38.0	(4.1)	38.1	(4.4)	37.9	(4.4)	0.708	0.709	36.6	(5.8)	37.8	(4.7)	38.2	(3.9)	< 0.001	0.003
Body mass index (overweight/ obese vs. healthy weight/underweight)	22.1		27.5		24.5		0.029	0.060	46.3		27.6		22.1		< 0.001	< 0.001
Smoking use (yes vs. no)	14.2		13.6		18.5		0.169	0.290	23.4		18.5		12.2		< 0.001	< 0.001
Alcohol consumption (yes vs. no)	75.6		68.8		71.4		0.004	0.009	39.6		62.0		79.0		< 0.001	< 0.001
Maternal depression	2.0	(3.7)	1.9	(3.5)	1.9	(3.6)	0.543	0.113	3.7	(5.9)	2.4	(4.1)	1.7	(3.3)	< 0.001	< 0.001
Maternal anxiety	0.9	(2.4)	1.0	(2.4)	0.8	(2.1)	0.573	0.313	2.3	(4.6)	1.0	(2.4)	0.8	(2.1)	< 0.001	< 0.001
Maternal stress	5.3	(5.6)	5.4	(5.7)	5.0	(5.0)	0.540	0.819	6.5	(6.9)	5.3	(5.6)	5.2	(5.4)	0.066	0.216
Mother-child attachment	0.28	(0.31)	0.29	(0.32)	0.34	(0.34)	0.038	0.027	0.36	(0.37)	0.30	(0.33)	0.28	(0.31)	0.047	0.070
Parental characteristics																
Financial situation							0.378	0.277							< 0.001	< 0.001
A lot to spare	27.3		25.4		28.9				13.1		19.0		30.6			
A little to spare	40.2		40.8		34.1				27.1		38.4		41.2			
Just enought	22.1		21.6		22.8				42.1		29.1		18.0			
To use the savings or go into the red	10.4		12.2		14.2				17.8		13.6		10.2			
Child characteristics																
Sex (female vs. male)	48.9		48.6		51.7		0.693	0.616	45.5		46.1		50.1		0.191	0.082
Number of siblings (≥ 1 vs. 0)	85.0		82.1		79.0		0.040	0.011	78.4		76.7		86.3		< 0.001	< 0.001
Time playing with computes/video games							0.208	0.474							0.009	0.010
0 h/day	55.5		58.9		55.7				49.5		54.9		58.1			
< 0.5 h/day	19.1		16.9		21.2				22.7		16.3		19.0			
0.5–1 h/day	21.3		18.3		18.9				17.5		22.6		18.7			
≥ 1/day	4.1		5.9		4.2				10.3		6.3		4.2			

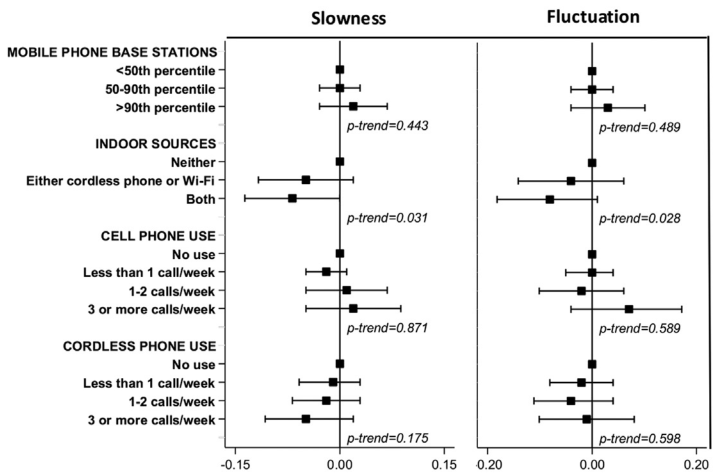
Values are percentages for the categorical variables and mean (standard deviation) for the continuous variables.
P-diff = P-value for differences; P-trend = P-value for trend.

Table 2.
Maternal, paternal, and child characteristics by personal cell phone and cordless phone use.

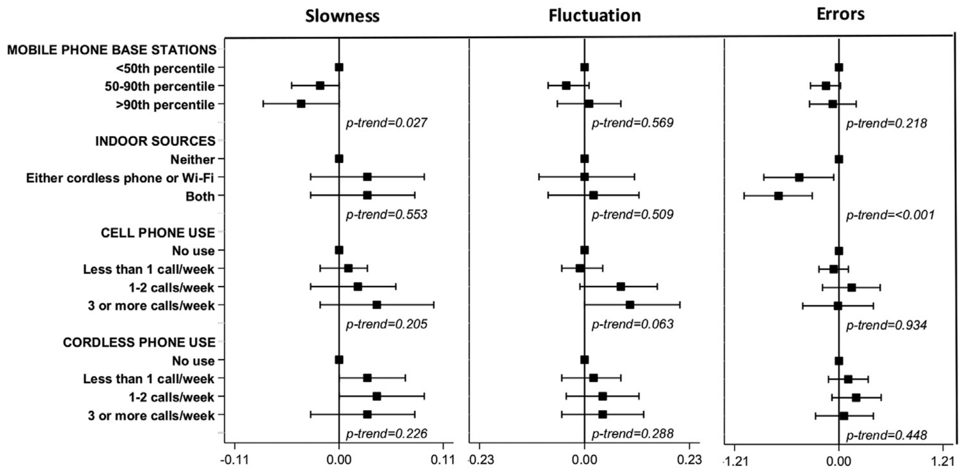
	Personal cell phone use						Personal cordless phone use					
	No use	Less than 1 call/ week	1-2 calls/week	3 or more calls/ week			No use	Less than 1 call/ week	1-2 calls/week	3 or more calls/ week		
	(n=1196)	**(n=863)**	**(n=147)**	**(n=95)**	***P*-diff**	***P*-trend**	**(n=314)**	**(n=1154)**	**(n=355)**	**(n=190)**	***P*-diff**	***P*-trend**
Maternal characteristics												
Education					0.001	< 0.001					< 0.001	0.004
High	73.8	73.2	67.3	54.3			71.2	78.2	72.8	61.1		
Medium	17.6	19.7	22.4	30.9			18.5	16.7	19.5	27.4		
Low	8.6	7.1	10.2	14.9			10.2	5.1	7.6	11.6		
% persons with low income in neighbourhood	36.0 (9.2)	36.1 (9.1)	36.2 (8.3)	39.5 (8.3)	0.007	0.009	36.5 (9.3)	36.0 (9.1)	35.1 (9.3)	36.4 (9.3)	0.210	0.445
Country of birth (non-Dutch vs. Dutch)	21.4	17.1	19.0	25.3	0.055	0.513	21.3	16.6	14.4	25.8	0.002	0.611
Age (years)	38.4 (4.2)	37.7 (4.1)	37.5 (4.4)	37.1 (4.4)	< 0.001	< 0.001	38.4 (4.0)	38.2 (4.0)	38.1 (3.9)	38.0 (3.9)	0.721	0.626
Body mass index (overweight/ obese vs. healthy weight/ underweight)	24.7	23.9	27.1	26.3	0.859	0.754	21.8	23.2	23.1	28.9	0.356	0.143
Smoking use (yes vs. no)	11.8	15.9	17.7	28.7	< 0.001	< 0.001	14.1	13.6	13.0	15.8	0.824	0.753
Alcohol consumption (yes vs. no)	71.5	76.0	69.8	65.9	0.044	0.996	70.7	77.3	77.0	71.0	0.044	0.835
Maternal depression	1.9 (3.7)	1.7 (3.2)	2.3 (4.2)	3.0 (4.2)	0.008	0.105	2.2 (3.7)	1.8 (3.3)	1.6 (3.4)	2.1 (3.4)	0.170	0.104
Maternal anxiety	0.9 (2.6)	0.8 (2.0)	1.2 (2.5)	1.3 (2.5)	0.132	0.083	1.1 (2.7)	0.7 (2.0)	0.8 (2.2)	1.1 (2.2)	0.026	0.254
Maternal stress	5.2 (5.6)	5.1 (5.3)	6.0 (6.2)	5.9 (6.2)	0.217	0.232	5.8 (6.1)	4.9 (5.1)	5.1 (5.8)	5.8 (5.8)	0.035	0.963
Mother-child attachment	0.29 (0.32)	0.28 (0.31)	0.30 (0.34)	0.32 (0.34)	0.774	0.961	0.30 (0.32)	0.28 (0.31)	0.29 (0.31)	0.30 (0.31)	0.808	0.976
Parental characteristics												
Financial situation					0.091	0.002					0.045	0.339
A lot to spare	27.9	26.6	25.7	19.4			26.8	27.9	33.0	23.3		
A little to spare	41.7	38.3	39.6	35.5			40.0	42.6	36.2	37.0		
Just enought	20.6	22.9	22.2	25.8			23.2	19.1	20.8	23.3		
To use the savings or go into the red	9.8	12.2	12.5	19.4			10.0	10.4	10.0	16.4		
Child characteristics												
Sex (female vs. male)	45.2	52.7	52.4	53.7	0.005	0.002	38.5	50.1	51.8	59.5	< 0.001	< 0.001
Number of siblings (≥ 1 vs. 0)	85.2	83.5	82.3	67.7	< 0.001	< 0.001	84.6	85.0	86.7	77.2	0.029	0.131
Time playing with computes/video games					< 0.001	0.003					< 0.001	0.010
0 h/day	58.8	57.2	46.0	50.0			56.2	59.5	57.3	44.3		
< 0.5 h/day	17.4	20.4	18.7	15.9			17.1	19.0	16.1	21.8		
0.5–1 h/day	19.5	18.1	27.3	20.7			20.7	18.2	23.0	24.1		
≥ 1/day	4.3	4.3	7.9	13.4			6.0	3.3	3.6	9.8		

Values are percentages for the categorical variables and mean (standard deviation) for the continuous variables.
P-diff=P-value for differences; P-trend=P-value for trend.

A. Speed of information processing



B. Inhibitory control



C. Cognitive flexibility

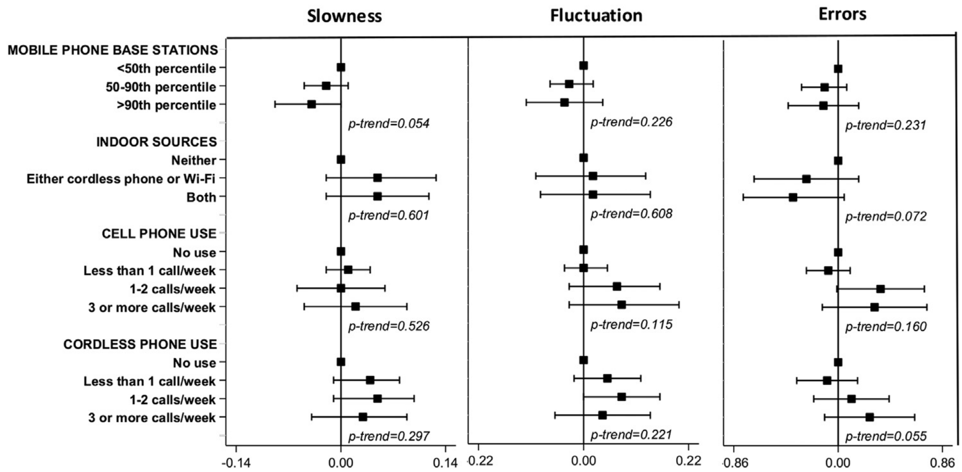


Fig. 1. Beta coefficient (95% Confidence Interval) from linear regression models. Higher values of each cognitive function measure indicate a poorer performance of the test reflecting a reduced cognitive function. Models were adjusted for maternal education, area-level indicator of socioeconomic position, country of birth, age, body mass index, tobacco use, alcohol consumption, depression, anxiety, and stress, mother-to-child attachment, parental financial situation, and child's sex, number of siblings, time playing with computers/video games, and age at cognitive test.

Fully-adjusted association between residential RF-EMF exposure from mobile phone base stations, presence of indoor sources of RF-EMF exposure at home, personal cell phone and cordless phone use, and speed of information processing, inhibitory control, and cognitive flexibility in 5–6 years old children.

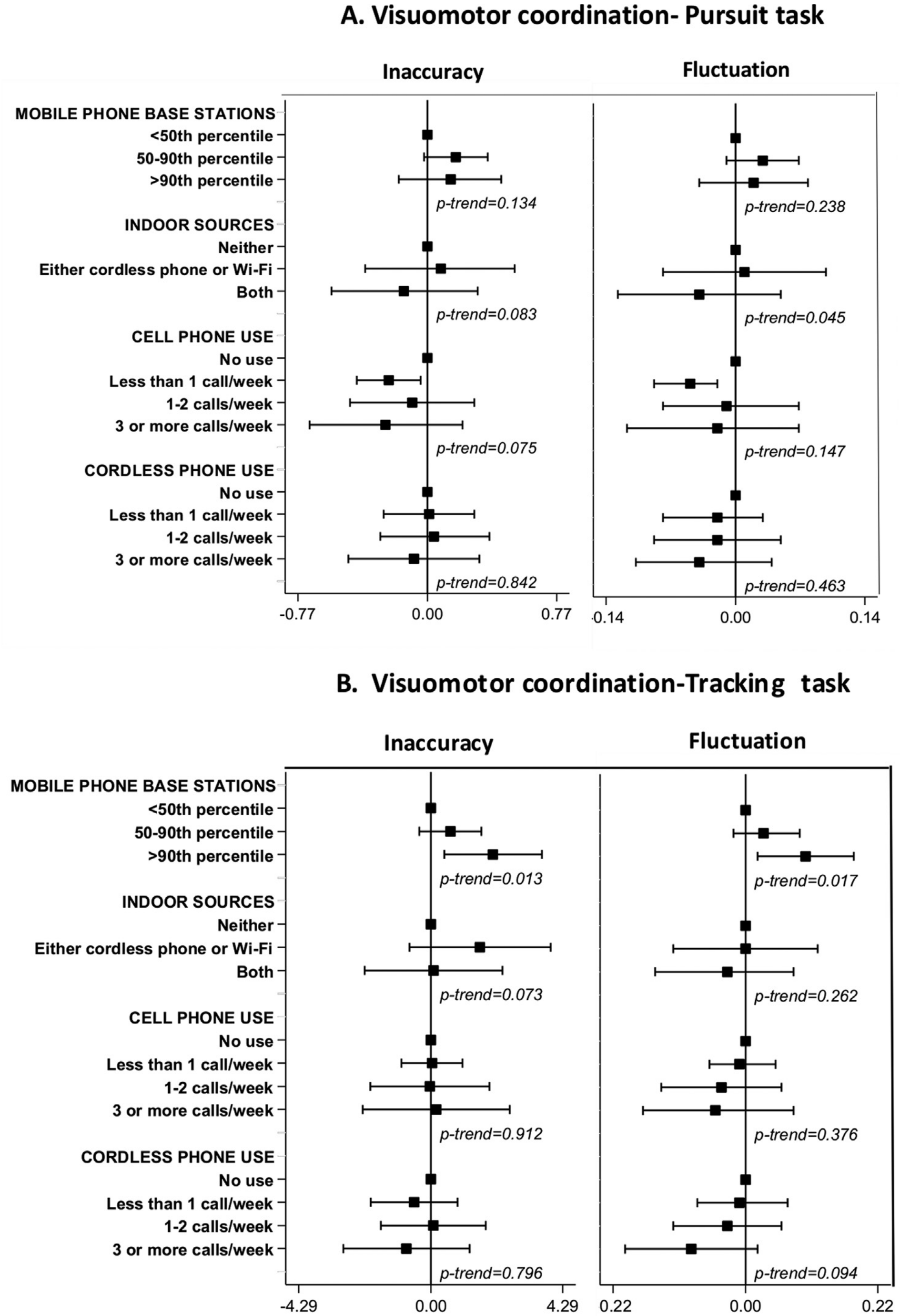


Fig. 2. Beta coefficient (95% Confidence Interval) from linear regression models. Higher values of each cognitive function measure indicate a poorer performance of the test reflecting a reduced cognitive function. Models were adjusted for maternal education, area-level indicator of socioeconomic position, country of birth, age, body mass index, tobacco use, alcohol consumption, depression, anxiety, and stress, mother-to-child attachment, parental financial situation, and child's sex, number of siblings, time playing with computers/video games, and age at cognitive test. Models of the tracking task were additionally adjusted for the total time to complete the task.
Fully-adjusted association between residential RF-EMF exposure from mobile phone base stations, presence of indoor sources of RF-EMF exposure at home, personal cell phone and cordless phone use, and speed of information processing, inhibitory control, and visuomotor coordination in 5–6 years old children.

and personal use of cell phone and cordless phone – on cognitive function in young children from a large population-based cohort study. We found that i) residential exposure to RF-EMF from mobile phone base stations was associated with an improved inhibitory control and cognitive flexibility, but a reduced visuomotor coordination; ii) presence of residential RF-EMF indoor sources was associated with an improved speed of information processing, inhibitory control, and visuomotor coordination; iii) personal cell phone use was associated with an improved visuomotor coordination; and iv) personal cordless phone use was associated with a reduced inhibitory control and cognitive flexibility.

The strengths of our study were the relative large sample size, the assessment of several RF-EMF exposure sources, the use of a standardized and validated exposure assessment method to estimate RF-EMF levels from mobile phone base stations, and the evaluation of four cognitive functions in young children using standardized and validated neuropsychological tests. Additionally, we were able to adjust the analyses for several potential confounding variables including socioeconomic, psychological, and lifestyle factors.

However, this study had some limitations that need to be taken into consideration for the interpretation of the results. A limitation of our study was its cross-sectional design. We were not able to explore associations between longitudinal and cumulative exposure to RF-EMF during early childhood and cognitive development at young ages. Another limitation is the potential residual confounding, although we adjusted our analyses for several potential confounding variables. The use of new technological devices such as smartphones and tablets among young children during daily life is increasing (Radesky et al., 2015). The use of mobile devices for other uses than calling could influence the results of all cognitive function computer tests due to training. In our study, personal cell phone use for calling at so young ages could be a proxy of a more general use of new telecommunication devices, explaining the observed improved visuomotor coordination. We adjusted our analyses for the daily time that children played with computer or video games, another activity that could influence the results of the cognitive function computer tests due to training, but we did not have information of uses others than calling of other technological devices such as tablets or smartphones. Residual confounding by socioeconomic position was less likely since children with a higher degree of cell phone use were more likely to live in a family with low socioeconomic position and families from high socioeconomic position are the ones more prone to be stimulating the cognitive function of their children (Osler et al., 2013). Conversely, residual confounding could influence the results of the association between presence of indoor RF-EMF exposure sources and cognitive function since families from high socioeconomic position were more prone to having WiFi or cordless phones at home and we observed an improved cognitive function on those children with more indoor RF-EMF exposure sources. Residual confounding, however, does not seem to play a major role in the analysis of the other two exposure variables: i) exposure to RF-EMF levels from mobile phone base stations at home was not strongly related to socioeconomic variables and ii) children with a higher degree of use of cordless phones were more likely from families of high socioeconomic position but showed an impaired cognitive function. Overall, our results may also be a result of chance findings since we performed a large number of analyses.

Among all RF-EMF sources assessed we could only estimate the exposure levels of RF-EMF from the mobile phone base stations. We used 1.5 m height for the RF-EMF modelling, instead of 1 m which would be closer to the average height of a 5 year old child, in order to be comparable with the 1.5 m height of RF-EMF measurements which is recommended in the CELENEC standard (CELENEC, 2008) and used previously by Bürgi et al. (2010) who found that it gave a robust estimate of indoor field strength. Other RF-EMF sources such as the presence of RF-EMF indoor sources and the personal use of cell phone and cordless phone can be seen as proxies of RF-EMF exposure but a personal exposure level cannot be estimated. The estimation of RF-EMF levels from outdoor sources was also limited to mobile phone base stations, even though there are more sources of outdoor RF-EMF, such as radio and TV broadcast stations. Nonetheless, mobile phone base stations represent the major source of environmental outdoor RF-EMF exposure (Bolte and Eikelboom, 2012; Roser et al., 2015). Indoor residential RF-EMF exposure sources and child's cell phone and cordless phone use at 5–6 years old was reported by the mothers at 7 years' follow-up and a differential recall bias related to the outcome could have been introduced. If so, this potential differential recall bias might be less probable for the cordless phone use than for the cell phone use since it has been shown that parents' perception of possible health risks from wireless phones may be greater for cell phones than cordless phones (Redmayne, 2013). However, since mothers did not know the results of the child's cognitive function tests assessed 1–2 years before, it is unlikely whether they could have systematically underestimated or overestimated the cell phone or cordless phone use report. Our study focused on the frequency of phone calls as proxy of RF-EMF exposure to the head, as well as on the use vs. the non-use of the phones for calling since children at 5–6 years had a very low number of calls. Although we also collected information on the duration of the cell phone and cordless phone calls, another relevant proxy of RF-EMF exposure to the head, we did not have enough contrast to explore its relationship with cognitive function (children only called for few minutes, 62–69% of the children reported <5 min/call on average for each phone). We did not collect information on use of speaker phone or hands free devices and location of the phone when calling, types of use that have an impact on the actual exposure levels of RF-EMF to the head. However, given the low frequency and duration of cell phone calls of the children of the study, we expect a very low use of speaker phone or hands free devices and location of the phone other than the head.

Previous studies on RF-EMF exposure and cognitive function have yielded inconclusive results. Regarding exposure to RF-EMF from mobile phone base stations, randomized double blind experimental studies investigated the relationship of short-term mobile phone base station radiation and cognitive function in adults and adolescents aged 15–16 years old, mainly showing no associations (Eltiti et al., 2009, 2007; Furubayashi et al., 2009; Regel et al., 2006; Riddervold et al., 2008; Roosli et al., 2010). However, these studies are not directly comparable to the results of our study in terms of the type of exposure assessed (short-term exposure instead of long-term exposure), in terms of the included population (adults and adolescents aged 15–16 years old instead of young children), and in terms of the setting where the cognitive function was evaluated (in a laboratory instead of in a more familiar environment such as the classroom). An observational cross-sectional study found an association between higher exposure to RF-EMF from mobile phone base stations in bedrooms and a faster reaction in the perceptual speed test in adults (Hutter et al., 2006). In contrast, in our study we did not find a relationship between higher exposure to RF-EMF from mobile phone base stations at home and speed of information processing but an improved inhibitory control and cognitive flexibility and a reduced visuomotor coordination. We have no explanation for these contradictory findings, although associations found in studies carried out in adults are not necessarily comparable to those carried out in young children as in our study. Previous observational studies have not assessed the presence of RF-EMF indoor sources such as cordless phone base stations and Wi-Fi on cognitive function. Regarding RF-EMF exposure from personal cell phone or cordless phone use, several studies have investigated the relationship of short-term RF-EMF exposure from cell phone on cognitive function in adults or children ages 10–14 years using a randomized double blind experimental design, reporting ambiguous results (Barth et al., 2008; Haarala et al., 2005; Preece et al., 2005; Regel and Achermann, 2011; Valentini et al., 2010). Also, results from experimental studies are not directly comparable with the results of observational studies as our study. Self-reported frequency of cell phone use in adolescents was associated with changes in some of the cognitive function test assessed one year later including working memory and learning, but not showing a clear direction of the association (Abramson et al., 2009; Thomas et al., 2010). A recent study carried out in children 8–11 years old found little evidence of a consistent association between cell phone or cordless phone use with specific cognitive functions including attentional function, working memory, and memory (Redmayne et al., 2016). Finally, another recent study investigating 10 year-old boys which performed spot measurements of electric fields in the 100 kHz to 6 GHz frequency range in the immediate surroundings of children's homes, a limited surrogate for individual exposure, showed associations between higher levels of RF-EMF exposure and impaired general cognitive and verbal development but not with specific cognitive functions such as attention, memory, visuomotor coordination, processing speed, or executive functions (Calvente et al., 2016). This was the first study which assessed a more global cognitive function measure including general cognitive development and verbal development, instead of assessing specific cognitive functions such as attentional or executive functions. Since we do not know what the biological mechanisms are for these potentially harmful exposures on the brain and which areas would be affected, it is difficult to include the assessment of the most appropriate cognitive functions in epidemiological studies. Of note, an improvement of the cognitive function would not necessarily mean beneficial long-term health effects and vice versa, a worsening of the cognitive function is not necessarily related to adverse long-term health effects. It is crucial to study and understand the biological mechanism behind these associations for a correct interpretation of the epidemiological results. In addition, each exposure source has different exposure characteristics: whereas personal cell phone and cordless phone use lead to localised exposures at the head of usually short duration, stationary outdoor and indoor sources result in more homogeneous whole-body and longer duration exposure of considerably lower RF-EMF levels (Health Protection Agency, 2012). Therefore, each exposure source could have qualitatively and quantitatively different effects on the brain. However, we would expect comparable results between the similar types of exposure sources, such as between personal cell phone and cordless phone use and between outdoor and indoor sources, which we did not find.

5. Conclusions

In conclusion, RF-EMF exposure from several sources including residential RF-EMF exposure from mobile phone base stations, presence of cordless phone base stations and Wi-Fi at home, as well as personal cell phone and cordless phone use did not show a consistent association with cognitive function in children aged 5–6 years. Although we assessed different sources of RF-EMF exposure, the development in future studies of an integrative RF-EMF exposure at different ages may be helpful to better understand the exact contribution of the different exposure sources to the RF-EMF dose received in the brain (Roser et al., 2015). Moreover, a better understanding of the potential biological mechanism behind the studied associations in the epidemiological studies is indispensable to interpret the results more precisely. In our study, given the lack of a biological mechanism of RF-EMF exposure behind these potential associations, we cannot discard that our results may be affected by residual confounding, or chance findings. Future studies need to tackle these potential limitations in more depth including an improved exposure assessment and an enhanced understanding on the possible biological mechanism.

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Ethics

Approval of the study was obtained from the Central Committee on Research involving Human Subjects in the Netherlands, the Medical Ethical Committees of the participating hospitals, and the Registration Committee of the Municipality of Amsterdam. The study was conducted in accordance with The Code Ethics of the World Medical Association (Declaration of Helsinki).

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.envres.2016.06.021.

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