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Link between Wi-Fi, cordless devices, mobile phone usage patterns, and behavioral problems among Japanese children: A prospective cohort study

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Abstract

Background: With the recent advent of technology, it is important to confirm the health and safety of the youth. This study aimed to prospectively evaluate the relationship between Wi-Fi, cordless phones, and mobile phone usage patterns and behavioral problems.

Methods: This study involved 2,465 children aged 8–17 years from the Hokkaido Study on Environment and Children's Health from October 2020 to January 2021, with a follow-up from September 2021 to March 2022. The mother–child dyad provided information on the presence of residential Wi-Fi and cordless phones, cordless phone call duration, and mobile phone usage pattern (duration of calls using mobile network and internet, online audio streaming, online video streaming, and playing online games) via a baseline questionnaire. Based on the scores on Strength and Difficulties Questionnaire at baseline and follow-up,the children were categorized into four groups: normal, persistent, improved, and concurrent.

Results: No significant association was found between Wi-Fi, mobile phone calls via mobile networks, and behavioral problems. Cordless phone at home had higher odds for improvement in total difficulty scores, and cordless phone for calling more than 4 minutes per week had lower odds of persistent problematic prosocial behavior. Longer duration of mobile phone calling via the internet (>40 min/week) had higher odds of concurrent total difficulties. Mobile phone calling via mobile network for <5 minutes per week had higher odds for improved total difficulty scores. Audio streaming via mobile phones for 60–120 minutes had lower odds of persistent total difficulties.

Conclusion: Our results showed sporadic findings between residential RF-EMF indoor sources and mobile phone usage pattern. These observed findings could be affected by residual confounding and chance findings. Ongoing follow-up studies are necessary to further explore this association through detailed exposure assessment and addressing the potential limitations of our study.

Keywords: Radiofrequency electromagnetic fields, Mobile phone, Children, Strength and difficulty questionnaire, Behavioral problems

1. Introduction

The recent rollout of 5G technology has raised concerns regarding its potential health impacts. The growing public apprehension is focused on the use of wireless devices, which are a significant source of radiofrequency electromagnetic fields (Schoeni et al., 2015). The ubiquitous presence of wireless communication devices among individuals, particularly children and adolescents, has raised concerns that they may cause behavioral problems. As lifetime exposure is longer in children and adolescents than in adults, it has been suggested that children are prone to environmental exposure because of their developing nervous systems (Rice and Barone, 2000; Schoeni et al., 2017). Exposure sources for radiofrequency electromagnetic radiation include outdoor sources (mobile phone base stations and broadcast antennas) and indoor sources (Wi-Fi, mobile phones, cordless phones, tablets, and laptops) (Guxens et al., 2019a). Near-field sources that are close to the body, such as mobile and cordless phones, account for the majority of radiofrequency electromagnetic fields (RF-EMF) exposure in the general population, particularly in the brain (Cabré-Riera et al., 2020; Eeftens et al., 2023; Eeftens et al., 2023; Roser et al., 2015; van Wel et al., 2021). Thus far, the current studies on potential biological effects of RF-EMF exposure do not draw firm conclusions, the World Health Organization has designated the neurodevelopmental impact of RF-EMF as a cause for concern. (Guxens et al., 2019).

In Japan; nearly two out of three children possess their own personal mobile phone (Okada et al.,2021). A recent survey of 3,364 parent–child dyads in Japan revealed that, among children aged 7–17 years, 81.3% of children had their own mobile device, the median age of first use and duration of use was 7 years and 5 years, respectively (Miyashita et al., 2023). Children frequently use mobile devices in today's digital landscape. Thus, research should shift from examining whether children use mobile technologies to exploring the hows, whys, and impact of their usage (George and Odgers, 2015).

According to American Psychiatric Association. (2013), "Behaviour problems refers to "Patterns of behaviour that are disruptive or inappropriate according to the societal norms and can negatively impact individuals functioning". Children with behavioral difficulties in their early years of life are prone to ongoing mental health issues (Fergusson et al., 2005; Jakobsen et al., 2012; Mistry et al., 2017). Behavioral problems are becoming prevalent in the younger generation, yet remain unidentified and untreated (Ajmal et al., 2022). Elementary school students showed more behavioral problems compared to junior and senior high school students in Japan and among specific problems, problematic prosocial behavior was most frequently reported (33.4%), followed by problems with peers (14.1%) and emotional symptoms (14.0%) (Miyashita et al., 2023). Few studies have focused solely on the persistence or change in behavioral problems, as the developmental changes in early childhood cause behavioral problems to be transient (D'Souza et al., 2019).

Previous studies exploring children's mobile phone usage duration as an index of RF-EMF and mental health have varied. Previous cross-sectional studies among adolescents investigated the possible link between RF-EMF and behavior problems. One study found that higher exposure to mobile telecommunication networks, measured using personal dosimeters, increased the risk for overall behavioral and conduct problems among German adolescents (Thomas et al., 2010), Self-reported data on mobile phone use among Swiss adolescents showed associations between increased mobile phone usage and overall behavior problems. (Roser et al., 2016). Findings from Amsterdam Born Children's development study found no association between duration of mobile and cordless phone calls with behavioral problems (Guxens et al., 2019). These cross-sectional studiesonly included mobile phone use for calling with behavioral problems and longitudinal studies are still missing.The use of mobile phones for gaming was associated with internalizing and total behavior problems (Calvente et al., 2016), while mobile phone use for entertainment (Zheng et al.,2014) has been associated with inattention. The discrepancy in these results could occur due to incomplete exposure assessment (assessing only mobile phone call duration and ignoring other usage metrices). Mobile phone and cordless phone call durations are considered to be the source of localized exposure to the brain (Roser et al., 2016) and other residential indoor RF-EMF sources; mobile phone use other than calling is considered a proxy with little contribution to RF-EMF exposure (Guxens et al., 2019). These usage metrics and the existence or lack of residential indoor RF-EMF sources will aid in separating the potential impact of RF-EMF from the use of the device itself.

To better understand RF-EMF exposure from different sources, near-field residential RF-EMF indoor sources, such as Wi-Fi, cordless, and mobile phone usage patterns, must be addressed. Therefore, this study aimed to separately assess the association of residential RF-EMF indoor sources (Wi-Fi, cordless phone) and mobile phone usage patterns, such as calling, audio streaming, video streaming on mobile phones with the change and persistence in behavioral problems over a year from a large birth cohort study in Japan.

2. Methods

2.1 Hokkaido Study on Environment and Children's Health and study participants

The primary goal of the prospective birth cohort, the Hokkaido Study on Environment and Children's Health was to assess the effects of perinatal chemical exposure on birth outcomes including neurobehavioral developmental disorders. The detailed Hokkaido cohort profile has been described previously (Kishi et al., 2013, 2017, 2021). Pregnant women visiting 37 hospitals in the Hokkaido Prefecture between 2003 and 2012 were recruited. This study was part of the Hokkaido Birth Cohort Study and included children aged 8–17 years. The baseline questionnaires regarding RF-EMF sources and usage, Strength and Difficulty Questionnaire (SDQ) (Goodman, 2001), and lifestyle were mailed to 5,221 participants between October 2020 and January 2021 based on random selection . We included a return envelope and a library card (worth 2000 yen) as a reward. A total of 3,364 questionnaires were completed (response rate of 64.4%). The follow-up survey was conducted approximately one year later, between September 2021 and March 2022, and received a total of 2,985 responses (88.7%). The procedure for data collection was similar to that of baseline. Of the 2,985, the following were excluded: 23 due to missing baseline SDQ data, 13 due to missing follow-up SDQ data, 46 due to twins (which caused a shared environment and gene/environment interaction), and 438 children due to missing response data. A total of 2,465 responses were therefore included for further analysis (Appendix Figure A.1).

Ethical approval was obtained from the Institutional Ethics Board for Epidemiological Studies at the Hokkaido University Graduate School of Medicine and Hokkaido University Center for Environment and Health Sciences (19-118). Informed consent was obtained from at least one parent before enrolment. All procedures were conducted in accordance with the Declaration of Helsinki.

2.2 Exposure Assessment

At baseline, we collected information on the presence or absence of residential RF-EMF indoor sources and mobile phone usage patterns from parent–child dyads.

2.2.1 Residential indoor RF-EMF sources

We collected data from parent–child dyads regarding the presence or absence of the main residential RF-EMF sources for children: Wi-Fi (No/Yes), cordless phones (No/Yes), and personal mobile phones (No/Yes)

2.2.2 Cordless phone use and mobile phone usage pattern

Information on cordless and mobile phone usage patterns was obtained from the questionnaire administered at baseline. Previous literature reported cordless and mobile phone calls and mobile data usage measures as major source of personal RF-EMF exposure and are the best exposure markers of RF-EMF (Eeften et al., 2023). The Mobile phone usage duration varies depending on the purpose.Therefore we used detailed mobile phone usage metrices including internet related activities (internet phone calls, online audio streaming, online video streaming, and playing online games) individually for analysis to clarify the individual usage effect on behaviour problem .

2.3 Outcome Assessment

2.3.1 Persistence and change in behavioral problems

Behavioral problems were measured at baseline and follow-up using the mother-reported Japanese version of the SDQ (Matsuishi et al., 2008). Parents were asked to respond to 25 items regarding their strengths and difficulties. Each item has three response categories: 0=not true, 1=somewhat true, and 2=certainly true. The subscales include conduct problems, hyperactivity, emotional symptoms, peer relationship problems, and prosocial behaviors. The four difficulty subscales (conduct problems, hyperactivity, emotional symptoms, and peer relationship) were summed up to obtain total difficulty scores ranging from 0 to 40 (Goodman, 2001). The prosocial behaviour subscale ranged between 0 to 10. We dichotomized the Japanese version of the SDQ at both baseline and follow-up as normal and borderline/clinical. Children scoring ≥13 were defined as borderline/clinical for total difficulty score and children scoring ≤5 as borderline/clinical for problematic prosocial behavior (Matsuishi et al., 2008).

2.3.2 Potential confounding variables

Several covariates were selected based on the results of previous studies and using directed acyclic graphs (Appendix Figure A.2). Children’s dates of birth and sex were obtained from medical records. Age was calculated based on the response date on the baseline questionnaire and categorized into elementary school (8–11 years) and, junior high school and higher (12–17 years). Parental information such as the mother’s smoking history during pregnancy, mother’s education, father’s education, and annual household income were obtained from the questionnaire at enrolment during maternal pregnancy (Kishi et al., 2013, 2017, 2021). Information on children’s overall health status, sleep, history of developmental support, and internet addiction were collected from a baseline questionnaire (October 2020 to January 2021). Children reported their overall health status as poor, fair, good, or excellent in the past week according to the KIDSCREEN-10 questionnaire (Nezu et al., 2016; Ravens-Sieberer et al., 2010). They also completed a modified internet addiction test comprising 11 items (Tobe et al., 2010) to assess internet addiction. Higher internet addiction scores indicate greater levels of internet addiction among children. Parents provided information regarding the child's sleep, that is, whether the child's overall sleep was good or not, and also reported whether any developmental support had been provided to the child in previous years by the local government or medical institutions.

2.3.3 Statistical handling

2.3.3.1 Cordless and mobile phone usage duration

Our sample showed no major difference in duration of cordless phone calls or mobile phone usage between weekdays and weekends, so we summed them to obtain total duration in a week. We categorized usage duration based on the distribution of the data as 1=no use, 2=< 50 percentile, 3=50–75 percentile, and 4=>75 percentile (Schoeni et al., 2017). Therefore, the duration of cordless phone calls and mobile phone for each usage were as follows: cordless phone call duration (1=no use, 2=<2 min/week, 3=2–4 min/week, 4=>4 min/week), mobile phone call duration using mobile network (1=no use, 2=<5 min/week, 3=5–15 min/week, 4=>15 min/week), mobile phone call duration using internet (1=no use, 2=< 10 min/week, 3=10–40 min/week, 4=>40 min/week), mobile phone use for online video streaming (1=no use, 2=<70 min/week, 3=70–180 min/week, 4=>180 min/week), mobile phone use for online audio streaming (1=no use, 2=<60 min/week, 3=60–120 min/week, 4=>120 min/week), and mobile phone use for playing online games (1=no use, 2=<60 min/week, 3=60–120 min/week, 4=>120 min/week). For sensitivity analysis, we collapsed the categories for each usage duration on the basis of median as 1=no use, 2=<50 percentile, 3=≥ 50 percentile.

2.3.3.2 Change and persistence in behavior problem (for longitudinal analysis)

As we were interested in persistence and changes in behavior problem, we created a composite measure of behavioral stability between baseline and follow-up. Children were categorized into the following groups based on the dichotomization at baseline and follow-up: no difficulties (normal at baseline and follow-up), persistent (borderline/clinical at baseline and follow-up), improved (borderline/clinical at baseline and normal at follow-up), and concurrent groups (normal at baseline and borderline/clinical at follow-up) (D'Souza et al., 2020).

2.3.3.3 Analysis

Two main analyses were conducted:

a. Cross-sectional association between exposure and behavior problems at baseline.

b. Longitudinal analysis between exposure at baseline and change and persistence in behavior problem at follow-up.

The descriptive characteristics of the children and parents were defined using frequencies, and simple associations with ageusing the chi-square test and analysis of variance (ANOVA). The chi-square test was used to determine the association between each exposure variable and age. We also performed Spearman's rank correlation test to explore the factors related to the total difficulty score and problematic prosocial behavior. For cross-sectional analysis multivariable logistic regression analysis was performed to explore association between each exposure variable with behaviour problem at base line (The ORs for borderline/clinical were calculated).

For longitudinal analysis, multinomial logistic regression was performed to explore the association between each exposure variable and persistence, change in the total difficulty score, and problematic prosocial behavior (The ORs for the persistent, concurrent, and improved groups were calculated). Among the exposure variables WiFi (having <5% of the data in some of the categories), and mobile phone usage duration for SMS (not related to RF-EMF exposure) were not further proceeded for analysis. The models were first run unadjusted and then adjusted for all potential confounding factors. The magnitude of the confounding in the adjusted models were identified according to Rothman's rule (Rothman et al., 2008). This rule states that if adding a confounder changes the effect estimates by 10% or more, it is considered strong confounder. *P*-trend was calculated using the ordinal scale of the cordless phone call duration and mobile phone usage duration variables in corresponding multinomial logistic regression models. For multiple comparisons, False Dicovery Rate (FDR) correction using Benjamini–Hochberg Procedure was used in both unadjusted and adjusted multinomial logistic regression. Statistical significance was set at $P < 0.05$. Analyses were performed using SAS (version 9.4; SAS Institute, Cary, NC, USA).

3. Results

3.1 Study Participants

Of the 2,465 participants with a mean age of 12 years, ranging from 8 to 17 years, 41.9% were elementary school and, 58.1% were junior high school and higher students. Table 1 displays the children's and parents' overall demographic characteristics, stratified by age. History of developmental support, self-reported health status, sleep, and Internet addiction differed significantly among age groups (p <.001) (Table 1). The percentage of elementary school children who received developmental support (12.5%) and reported their overall health status as excellent (65.2%) was higher than junior high school and higher children. The mean of Internet addiction was also higher among junior high school children (20.0±5.84) than elementary school

(17.7±5.79). Of the participants, 46.0% belonged to families with an annual household income of 3.0–4.9 million yen per year at birth.

Table 1. Demographic characteristics of the participants at baseline

Items	Category	Total (n=2465)		Age				
				Elementary school (n=1032)		Junior high school and higher (n=1433)		*P*
		n	%	n	%	n	%	
Child age at survey (Mean ± SD)		12.7 ± 2.4		10.3 ± 0.99		14.4 ± 1.42		<.001
Sex	Boys	1214	49.3	519	50.3	695	48.5	.380
	Girls	1251	50.7	513	49.7	738	51.5	
Developmental support [a]	No	2209	89.6	903	87.5	1306	91.1	.003
	Yes	256	10.4	129	12.5	127	8.9	
Self-reported health status	Poor	7	0.2	3	0.3	4	0.3	<.001
	Fair	70	2.8	16	1.5	54	3.8	
	Good	926	37.6	340	33.0	586	40.9	
	Excellent	1462	59.3	673	65.2	789	55.0	
Sleep well	No	646	26.2	173	16.7	473	33.0	<.001
	Yes	1819	73.8	859	83.3	960	67.0	
Mother's smoking during pregnancy [b]	Do not Smoke	1729	70.1	727	70.4	1002	69.9	.893
	Quit smoking	574	23.3	240	23.3	334	23.3	
	Smoke	162	6.6	162	6.6	97	6.8	
Mother's Education [b]	≤9	68	2.8	33	3.2	35	2.4	.262
	10-12	932	37.8	389	37.7	543	37.9	
	13 - 15	1108	45.0	448	43.4	660	46.1	
	> 16	357	14.5	162	15.7	195	13.6	
Father's Education [b]	≤9	134	5.4	61	5.9	73	5.1	.635
	10-12	878	35.6	365	35.4	513	35.8	
	13 - 15	645	26.1	278	26.9	367	25.6	
	> 16	808	32.8	328	31.8	480	33.5	
Annual Household Income	< 3.0	458	18.6	206	20.0	252	17.6	.128

	3.0 - 4.9	1133	46.0	485	47.0	648	45.2	
	5.0 - 7.9	665	27.0	264	25.6	401	28.0	
	≥ 8	209	8.4	77	7.4	132	9.2	
Internet addiction (Mean ± SD)		19.0±5.93		17.7 ± 5.79		20.0 ± 5.84		<.001

[a] At baseline, mothers answered whether child had received developmental support by the government or medical institution.

[b] Information was obtained from a questionnaire at enrollment during maternal pregnancy.

3.1.1 Exposures

Table 2 shows the descriptive characteristics of exposure in the total sample stratified by age. A total of 67.4% of children did not possess personal mobile phones.Additionally, 97.9% and 15.4% of children reported having Wi-Fi and cordless phone at home, respectively. The average duration of mobile network phone calls was 22.2 minutes per week and internet call duration was 43.6 minutes per week. The average duration of online audio streaming, video streaming, and online games were 85.9, 115.7, and 82.4 minutes per week. The longer duration of mobile phone usage was longer among Junior high and higher age group particularly the activities while connected to the Internet.

The correlation between exposure variables was between -0.01 to 0.98, with different level of statistical significance. There was moderate correlation between usage measures that used the internet (mobile phone call duration using the internet, mobile use duration for online audio streaming, online video streaming, and playing online games) ranging between 0.39 to 0.50 with statistical significance of <0.001. (Figure 1)

Insert Figure 1 here

Table 2. Descriptive statistics of exposure measures at baseline

Items	Category	Total (n=2465)		Age: Elementary school (n=1032)		Age: Junior high school and higher(n=1433)		*P*
		n	%	n	%	n	%	
Wi-Fi	No	52	2.1	26	2.5	26	1.8	.229
	Yes	2413	97.9	1006	97.5	1407	98.2	
Cordless	No	2085	84.6	857	83.0	1228	85.7	.072
	Yes	380	15.4	175	17.0	205	14.3	
Mobile phone	No	1662	67.4	702	68.0	960	67.0	.590
	Yes	803	32.6	330	32.0	473	33.0	
Mobile phone calls duration using mobile network (n= 2398)	None	1662	69.3	702	70.0	960	68.8	<.001
	< 5 min/week	303	12.6	162	16.1	141	10.1	
	5–15 min/week	268	11.2	104	10.4	164	11.8	
	> 15 min/week	165	6.9	35	3.5	130	9.3	
Cordless phone calls duration (n = 2402)	None	2085	86.8	857	84.8	1228	88.2	.050
	< 2 min/week	105	5.4	51	5.1	54	3.8	
	2–4 min/week	129	5.3	67	6.6	62	4.5	
	> 4 min/week	83	3.5	35	3.5	48	3.5	
Mobile phone calls duration using internet (n =2246)	None	959	42.7	572	61.6	387	29.4	<.001
	< 10 min/week	620	27.6	254	27.3	366	27.8	
	10–40 min/week	343	15.3	73	7.9	270	20.5	
	> 40 min/week	324	14.4	30	3.2	294	22.3	
Mobile phone use for video streaming using internet (n =1970)	None	578	29.3	326	42.8	252	20.9	<.001

	< 70 min/week	682	34.6	317	41.6	365	30.2	
	70–180 min/week	437	22.2	81	10.6	356	29.5	
	> 180 min/week	273	13.9	38	5.0	235	19.4	
Mobile phone use for audio streaming using internet (n = 2379)	None	1114	51.2	675	74.3	439	34.7	<.001
	< 60 min/week	502	23.1	174	19.2	328	25.9	
	60–120 min/week	348	16.0	46	5.0	302	23.8	
	> 120 min/week	210	9.7	13	1.4	197	15.6	
Mobile phone use for online games (n = 2318)	None	1030	53.4	449	61.5	581	48.4	<.001
	< 60 min/week	427	22.1	210	28.8	217	18.0	
	60–120 min/week	289	15.0	47	6.4	242	20.2	
	> 120 min/week	184	9.5	24	3.3	160	13.3	
Mobile phone use duration for SMS	None	2016	82.4	846	82.9	1170	82.0	<.001
	< 10 min/week	191	7.8	117	11.5	74	5.2	
	10–30 min/week	140	5.7	49	4.8	91	6.4	
	> 30 min/week	100	4.1	9	0.9	91	6.4	

SMS, short service message

3.1.2 Outcomes

There was a significant moderate correlation between SDQ scores at baseline and follow-up (Appendix Table A.2). At baseline, 14.8% of the children scored for high (borderline/clinical) total difficulty score, whereas at the follow-up, it reduced to 9.6%. However, the percentage of children with high (borderline/clinical) problematic prosocial behavior group at baseline was 33.3%, which increased to 40.6% at the follow-up (Appendix Table A.2). Among the specific behavioral problems, problematic prosocial behavioral problems were the most commonly reported both at the baseline and follow-up (33.3%, 40.6%), followed by emotional symptoms (14.3%, 15.4%), peer relationship problems (14.0%, 15.6%), and conduct problems (9.6%, 9.2%) (Appendix Table A.2).

Table 3 shows four separate profiles for behavioral problems based on change and persistence over a year. Of those who scored in normal range at baseline for total difficulty scores, 78.6% remained in this range, whereas only 51.7% for problematic prosocial behavior remained in normal range. Persistence in problematic prosocial behavior was higher (24.5%) compared to other behavioral problems and total difficulty scores over one year. The dynamics of shifts in profiles were higher among junior high and higher age group for total difficulty scores and other subscales, except for emotional symptoms.

Table 3. Frequency distribution of behavioral categorization

	Category	Total (n=2465)	Age				
			Elementary school (n=1032)		Junior high school and higher(n=1433)		*P*
Items		n (%)	n	(%)	n	(%)	
Conduct problems	Normal group	2124 (86.2)	1001	82.5	1123	89.8	<.001
	Persistent group	123 (5.0)	79	6.5	44	3.5	
	Improved group	114 (4.6)	73	6.0	41	3.3	
	Concurrent group	104 (4.2)	61	5.0	43	3.4	
Emotional symptoms	Normal group	1912 (77.6)	970	79.9	942	75.3	.004
	Persistent group	178 (7.2)	66	5.4	112	8.9	
	Improved group	174 (7.0)	86	7.1	88	7.1	
	Concurrent group	201 (8.2)	92	7.6	109	8.7	
Peer problems	Normal group	1917 (77.7)	923	76.1	994	79.5	.083
	Persistent group	180 (7.3)	101	8.3	79	6.3	
	Improved group	163 (6.6)	90	7.4	73	5.8	
	Concurrent group	205 (8.3)	100	8.2	105	8.4	

Hyperactivity-Inattention	Normal group	2112 (85.7)	971	80.0	1141	91.2	<.001
	Persistent group	140 (5.7)	109	9.0	31	2.5	
	Improved group	106 (4.3)	73	6.0	33	2.6	
	Concurrent group	107 (4.3)	61	5.0	46	3.7	
Prosocial behavior	Normal group	1274 (51.7)	555	45.7	719	57.4	<.001
	Persistent group	605 (24.5)	364	30.0	241	19.3	
	Improved group	215 (8.7)	115	9.5	100	8.0	
	Concurrent group	371 (15.0)	180	14.8	191	15.3	
Total Difficulties	Normal group	1939 (78.6)	911	75.1	1028	82.2	<.001
	Persistent group	212 (8.6)	127	10.5	85	6.8	
	Improved group	154 (6.2)	88	7.2	66	5.3	
	Concurrent group	160 (6.5)	88	7.2	72	5.7	

Normal (normal at baseline and follow-up); persistent (borderline/clinical at baseline and follow-up); improved (borderline/clinical at baseline and normal at follow-up); and concurrent (normal at baseline and borderline/clinical at follow-up).

3.1.3 Association among RF-EMF indoor residential sources, mobile phone use, and behavioral problems.

In the cross-sectional analysis we found that longer duration of cordless phone calls (>4 min/week) was associated with lower odds of problematic prosocial behavior, and playing online games for < 60 min/week had lower odds of problematic prosocial behavior compared to non-users. Moderate mobile phone call duration (10–40 min/week) using internet and moderate audio streaming for 60–120 minutes had lower odds for total difficulties compared to non-users (Table 4). Tables 5 and 6 show the longitudinal associations between residential RF-EMF indoor sources, mobile phone usage patterns, and change and persistence in behavior.In adjusted models, we found that children having cordless at home had higher odds of improving their total difficulty score (OR 1.88, 95% CI 1.24–2.85) (Table 5) compared to non-users. Moderate mobile phone call duration using internet (10–40 minutes per week) were less likely to be in the persistent group. However, those who used the phones for more than 40 minutes per week were more likely to be in the concurrent group (OR 2.01, 95% CI 1.14 3.57) compared to non-users (Table 5). Shorter duration of mobile phone calls using networks (< 5 min/week) had higher odds of being in the improved group (OR 1.60, 95% CI 1.01–2.53) compared to non-users (Table 5). Children who used mobile phones for audio streaming for 60–120 minutes had lower odds of being in the persistent group (OR 0.53, 95% CI 0.30–0.93) (Table 5). In the adjusted models for problematic prosocial behavioral problems, we found no significant association, except for cordless phone call duration. Children who used cordless phone for calling more than 4 minutes per week had lower odds of persistent problematic prosocial behavior problem (OR 0.42, 95% CI 0.21–0.86) compared to non-users (Table 6). In sensitivity analysis using collapsed categories of exposure variables, we only found consistent results for audio streaming for ≥ 60 min/week, which had lower odds for persistent total difficulties (Appendix Table A.6. and A.7.).

We observed a significant association between longer duration of mobile phone use for online games, video streaming, and audio streaming with persistent total difficulty scores and problematic prosocial behavior in the unadjusted models (Appendix Table A.3. and A.4.). These associations diminished after adjusting for potential confounding variables, and internet addiction was identified as a strong confounding variable according to Rothman's rule (Rothman et al., 2008).

Table 4. Cross-sectional (baseline) association among Residential RF-EMF indoor sources, mobile phone use, and behavioral problems

	Total Difficulty Score				**Problematic Prosocial Behavior**			
	Unadjusted Model		**Adjusted Model[a]**		**Unadjusted Model**		**Adjusted Model[a]**	
	OR	(95% CI)	OR	(95% CI)	OR	(95% CI)	OR	(95% CI)
Wi-Fi								
No	Reference		Reference		Reference		Reference	
Yes	0.64	0.32–1.26	0.65	0.32–1.34	1.12	0.62–2.03	0.99	0.54–1.82
Cordless								
No	Reference		Reference		Reference		Reference	
Yes	1.11	0.82–1.50	1.35	0.97–1.88	0.77	0.61–0.98	0.83	0.65–1.07
Mobile phone								
No	Reference		Reference		Reference		Reference	
Yes	1.13	0.89–1.43	1.08	0.84–1.39	0.98	0.82–1.17	0.97	0.80–1.16
Mobile phone calls duration using mobile network								
None	Reference		Reference		Reference		Reference	
< 5 min/week	1.09	0.78–1.54	1.07	0.74–1.55	1.17	0.90–1.50	1.23	0.94–1.60
5–15 min/week	0.98	0.68–1.43	0.89	0.59–1.33	0.94	0.71–1.24	0.92	0.69–1.23
> 15 min/week	1.38	0.91–2.09	1.39	0.89–2.18	0.94	0.67–1.32	0.84	0.59–1.19
Cordless phone calls duration								
None	Reference		Reference		Reference		Reference	
< 2 min/week	0.89	0.50–1.59	1.2	0.65–2.22	0.73	0.47–1.14	0.81	0.52–1.28
2–4 min/week	1.20	0.74–1.92	1.44	0.86–2.41	1.07	0.73–1.55	1.15	0.78–1.69
> 4 min/week	1.39	0.79–2.43	1.34	0.72–2.48	0.42	0.24–0.75**	0.43	0.24–0.77**

Mobile phone calls duration using internet								
None		Reference		Reference		Reference		Reference
< 10 min/week	0.97	0.73–1.28	0.99	0.73–1.35	1.00	0.80–1.24	0.88	0.70–1.10
10–40 min/week	0.66	0.45–0.96*	0.65	0.42–0.99*	1.13	0.87–1.47	0.89	0.67–1.19
> 40 min/week	0.99	0.70–1.40	1.04	0.69–1.58	1.27	0.97–1.65	0.89	0.66–1.21
Mobile phone use for video streaming using internet								
None		Reference		Reference		Reference		Reference
< 70 min/week	1.00	0.73–1.37	1.04	0.74–1.47	1.15	0.91–1.46	1.07	0.84–1.37
70–180 min/week	0.99	0.70–1.41	1.00	0.67–1.49	1.20	0.92–1.57	0.96	0.72–1.28
> 180 min/week	1.05	0.70–1.57	0.93	0.59–1.47	1.46	1.08–1.97*	1.02	0.73–1.42
Mobile phone use for audio streaming using internet								
None		Reference		Reference		Reference		Reference
< 60 min/week	0.77	0.57–1.04	0.88	0.62–1.24	0.93	0.74–1.17	0.86	0.67–1.09
60–120 min/week	0.57	0.39–0.84**	0.56	0.35–0.87*	1.11	0.86–1.43	0.85	0.64–1.14
> 120 min/week	1.07	0.72–1.58	1.14	0.71–1.84	1.40	1.03–1.89*	1.06	0.75–1.50
Mobile phone use for online games								
None		Reference		Reference		Reference		Reference
< 60 min/week	1.38	1.00–1.90	1.05	0.73–1.50	0.96	0.75–1.22	0.73	0.56–0.95*
60–120 min/week	1.08	0.73–1.60	0.93	0.60–1.44	1.29	0.98–1.69	0.86	0.64–1.16
> 120 min/week	2.05	1.38–3.05***	1.44	0.91–2.29	1.39	1.00–1.92	0.78	0.55–1.12

p*-value <0.05, ***p*-value<0.01,**p*-value<0.001

[a] Adjusted for age, sex, self-reported health status, history of developmental support, sleep, mother's education, annual household income, and internet addiction

Table 5. Association of RF-EMF exposure sources and mobile phone use with persistence and change in behavior problems (Adjusted model).

	Total Difficulty Score (n=2465)											
	Adjusted Model[a]											
	Persistent group				Improved group				Concurrent group			
	N	OR (95% CI)	*P*	Adjusted *P* [b]	N	OR (95% CI)	*P*	Adjusted *P* [b]	N	OR (95% CI)	*P*	Adjusted *P* [b]
Cordless												
No	186	Reference			119	Reference			132	Reference		
Yes	26	1.00 (0.63–1.60)	.973	.973	35	**1.88 (1.24–2.85)**	**.002**	**.006**	28	1.32 (0.85–2.05)	.207	.270
Mobile phone												
No	144	Reference			94	Reference			101	Reference		
Yes	68	0.96 (0.69–1.33)	.808	.865	60	1.33 (0.94–1.88)	.107	.169	59	1.23 (0.87–1.73)	.233	.304
Mobile phone calls duration using mobile network (n= 2398)												
None	144	Reference			94	Reference			101	Reference		
< 5 min/week	19	0.72 (0.42–1.23)	.237	.386	28	**1.60 (1.01–2.53)**	.043	.097	22	1.15 (0.70–1.88)	.572	.644
5–15 min/week	25	0.95 (0.58–1.56)	.851	.892	13	0.84 (0.46–1.56)	.597	.644	20	1.21 (0.72–2.02)	.458	.550
> 15 min/week	18	1.34 (0.76–2.37)	.306	.408	13	1.46 (0.77–2.73)	.238	.386	9	0.98 (0.48–2.02)	.970	.970
P-trend		.208				.594				.937		
Cordless phone calls duration (n=2402)												
None	186	Reference			119	Reference			132	Reference		
< 2 min/week	5	0.81 (0.31–2.11)	.668	.741	9	1.78 (0.85–3.74)	.123	.223	9	1.60 (0.77–3.31)	.204	.307
2–4 min/week	11	1.27 (0.63–2.54)	.501	.601	11	1.71 (0.87–3.35)	.116	.221	9	1.16 (0.56–2.39)	.679	.741
> 4 min/week	8	1.13 (0.49–2.60)	.764	.809	8	1.70 (0.77–3.76)	.188	.299	6	1.29 (0.54–3.11)	.560	.650

P-trend		.427				.438				.930		
Mobile phone calls duration using internet (n =2246)												
None	98	Reference			54	Reference			54	Reference		
< 10 min/week	46	0.76 (0.50–1.14)	.191	.300	50	1.52 (1.00–2.32)	.047	.095	46	1.45 (0.95–2.23)	.082	.141
10–40 min/week	20	**0.50 (0.28–0.88)**	**.016**	**.036**	18	0.92 (0.51–1.67)	.803	.860	18	1.06 (0.59–1.71)	.835	.860
> 40 min/week	30	1.01 (0.59–1.71)	.966	.966	21	1.33 (0.73–2.43)	.342	.440	26	**2.01 (1.14–3.57)**	**.015**	**.036**
P-trend		.331				.639				.372		
Mobile phone use for video streaming using internet (n =1970)												
None	52	Reference			33	Reference			44	Reference		
< 70 min/week	55	0.92 (0.59–1.42)	.721	.763	46	1.19 (0.74–1.91)	.471	.649	48	0.92 (0.59–1.42)	.716	.763
70–180 min/week	36	0.86 (0.52–1.44)	.582	.748	28	1.05 (0.60–1.85)	.849	.849	19	0.56 (0.31–1.00)	.053	.128
> 180 min/week	27	0.88 (0.50–1.56)	.675	.763	15	0.85 (0.43–1.69)	.655	.763	14	0.58 (0.29–1.14)	.116	.245
P-trend		.644				.546				.025		
Mobile phone use for audio streaming using internet (n=2379)												
None	113	Reference			72	Reference			76	Reference		
< 60 min/week	38	0.82 (0.53–1.28)	.395	.474	29	0.99 (0.61–1.59)	.976	.976	34	1.08 (0.69–1.70)	.706	.770
60–120 min/week	23	**0.53 (0.30–0.93)**	**.027**	**.070**	13	0.56 (0.28–1.10)	.097	.177	20	0.83 (0.46–1.48)	.533	.619
> 120 min/week	16	0.75 (0.39–1.44)	.386	.474	21	1.68 (0.90–3.13)	.100	.177	9	0.68 (0.31–1.51)	.353	.459
P-trend		.122				.935				.221		
Mobile phone use for online games (n=1930)												
None	69	Reference			57	Reference			70	Reference		
< 60 min/week	40	1.00 (0.62–1.61)	.980	.980	29	1.02 (0.62–1.68)	.914	.968	29	0.77 (0.48–1.25)	.300	.446
60–120 min/week	22	0.90 (0.51–1.60)	.735	.853	16	0.86 (0.46–1.61)	.651	.781	15	0.62 (0.33–1.16)	.136	.273
> 120 min/week	23	1.36 (0.74–2.48)	.310	.446	18	1.54 (0.81–2.91)	.181	.322	14	0.91 (0.47–1.79)	.801	.874
P-trend		.649				.588				.543		

Significant results are shown in bold.
[a] Adjusted for age, sex, self-reported health status, history of developmental support, sleep, mother's education, annual household income, and internet addiction.
[b] False Dicovery Rate (FDR) correction using Benjamini–Hochberg Procedure was used.

Table 6. Association of electromagnetic fields exposure sources and mobile phone use with persistence and change in prosocial behavior problems (Adjusted model).

	Problematic Prosocial Behavior											
	Adjusted Model[a]											
	Persistent group				Improved group				Concurrent group			
	N	OR (95% CI)	*P*	Adjusted p^b	N	OR (95% CI)	*P*	Adjusted p^b	N	OR (95% CI)	*P*	Adjusted p^b
Cordless												
No	522	Reference			189	Reference			312	Reference		
Yes	83	0.84 (0.63–1.11)	.262	.341	26	0.71 (0.46–1.10)	.219	.328	59	0.97 (0.70–1.33)	.706	.810
Mobile phone												
No	408	Reference			147	Reference			256	Reference		
Yes	197	0.96 (0.78–1.19)	.739	.739	68	0.91 (0.67–1.25)	.597	.660	115	0.89 (0.69–1.15)	.389	.454
Mobile phone calls duration using mobile network												
None	408	Reference			147	Reference			256	Reference		
< 5 min/week	85	1.33 (0.99–1.81)	.058	.132	27	1.12 (0.71–1.75)	.620	.689	47	1.13 (0.79–1.63)	.487	.571
5–15 min/week	67	0.92 (0.67–1.27)	.638	.689	19	0.72 (0.43–1.21)	.228	.342	34	0.75 (0.50–1.13)	.172	.273
> 15 min/week	35	0.71 (0.46–1.08)	.111	.187	18	1.09 (0.63–1.88)	.748	.763	23	0.79 (0.48–1.28)	.344	.434
P-trend		.018				.427				.070		
Cordless phone calls duration												
None	522	Reference			189	Reference			312	Reference		
< 2 min/week	25	0.93 (0.57–1.53)	.795	.858	4	0.44 (0.14–1.13)	.086	.179	17	1.03 (0.59–1.80)	.916	.915

2–4 min/week	32	0.99 (0.63–1.55)	.981	.981	14	1.17 (0.64–2.14)	.606	.712	14	0.72 (0.39–1.30)	.277	.394
> 4 min/week	10	**0.42 (0.21–0.86)**	**.017**	**.048**	5	0.58 (0.22–1.49)	.260	.391	20	1.36 (0.79–2.34)	.258	.391
P-trend		.105				.497				.923		
Mobile phone calls duration using internet												
None	224	Reference			82	Reference			139	Reference		
< 10 min/week	150	0.92 (0.71–1.19)	.547	.642	48	0.86 (0.58–1.27)	.463	.596	101	1.08 (0.80–1.46)	.589	.663
10–40 min/week	94	0.96 (0.69–1.33)	.838	.870	25	0.79 (0.47–1.33)	.386	.521	53	0.99 (0.67–1.45)	.958	.958
> 40 min/week	87	0.82 (0.58–1.16)	.276	.414	34	1.06 (0.64–1.74)	.819	.870	41	0.75 (0.48–1.16)	.200	.338
P-trend		.563				.956				.220		
Mobile phone use for video streaming using internet												
None	123	Reference			52	Reference			94	Reference		
< 70 min/week	174	1.10 (0.83–1.47)	.485	.623	54	0.83 (0.55–1.26)	.393	.544	94	0.82 (0.59–1.14)	.255	.445
70–180 min/week	111	0.94 (0.67–1.31)	.719	.808	39	0.87 (0.53–1.40)	.570	.700	65	0.81 (0.55–1.19)	.296	.470
> 180 min/week	77	1.00 (0.68–1.48)	.973		29	1.02 (0.59–1.76)	.934	.970	42	0.89 (0.56–1.41)	.642	.754
P-trend		.550				.863				.693		
Mobile phone use for audio streaming using internet												
None	265	Reference			99	Reference			165	Reference		
< 60 min/week	118	0.85 (0.65–1.13)	.277	.469	39	0.79 (0.52–1.19)	.265	.469	72	0.88 (0.64–1.22)	.462	.567
60–120 min/week	93	0.85 (0.61–1.19)	.359	.510	29	0.80 (0.48–1.32)	.393	.531	54	0.92 (0.62 -1.37)	.713	.762
> 120 min/week	64	1.13 (0.75–1.68)	.547	.642	21	1.10 (0.61–1.98)	.734	.762	33	1.06 (0.65–1.71)	.812	.812
P-trend		.671				.778				.754		
Mobile phone use for online games												
None	236	Reference			89	Reference			151	Reference		
< 60 min/week	100	0.76 (0.56–1.03)	.078	.177	31	0.66 (0.41–1.04)	.076	.177	67	0.96 (0.68–1.35)	.818	.921

60–120 min/week	79	0.80 (0.57–1.13)	.217	.309	29	0.91 (0.55–1.49)	.720	.846	36	0.76 (0.49–1.18)	.235	.317
> 120 min/week	62	1.02 (0.68–1.54)	.890	.962	10	0.52 (0.25–1.10)	.089	.177	37	1.39 (0.87–2.24)	.165	.248
P-trend		.778				.513				.747		

Significant results are shown in bold.
[a] Adjusted for age, sex, self-reported health status, history of developmental support, sleep, mother's education, annual household income, and internet addiction.
[b] False Dicovery Rate (FDR) correction using Benjamini–Hochberg Procedure was used.

4. Discussion

This study explored the association between self-reported residential RF-EMF indoor sources and various mobile usage measures with behavior problem, applying cross-sectional and longitudinal approach. We observed sporadic and inconsistent significant associations between RF-EMF exposure markers and behavioral problems. We found that the presence of a cordless phone at home, shorter duration of mobile phone calls using networks for calls (<5 minutes per week), moderate internet calling (10–40 minutes per week), and moderate audio streaming (60–120 mins/week) showed protective effects for total difficulties. However, a longer duration of internet calls (> 40 min/week) showed a possible impact on behavioral problems. Audio streaming (60–120 mins/week) had shown consistent results in cross-sectional and longitudinal analysis regarding the protective effect on total difficulties; longer cordless phone calls (>4 min/week) also had lower odds for problematic prosocial behavior. The other significant associations were not consistent and were probably due to chance given the number of associations tested. At 0.05 significance, we would expect 6 out of the 120 associations tested in the multinomial logistic regression model to be significant (Tables 5 and 6). In our analysis, we observed exactly six significant ORs (five for total difficulty and one for problematic prosocial behavior). Therefore, our results may be attributable to chance rather than being true associations. To the best of our knowledge, this is the first study in Japan to investigate the association between residential indoor RF-EMF sources and mobile phone usage patterns with changes in and persistence of behavioral problems. In contrast to previous longitudinal studies (Roser et al., 2016; Sudan et al., 2016), we investigated the change and persistence in behavioral problems; therefore, we included a group of children who newly developed behavioral difficulties, in addition to those who already had behavioral difficulties, and who improved during the follow-up.

Our findings regarding the protective effect of a mobile phone duration of less than 5 minutes per week suggest that the short duration of the device has no harmful effect on total difficulty scores, which is consistent with previous findings among Japanese children who used mobile phones for less than 1 hour and had lower odds of total difficulty compared to non-users (Okada et al., 2021). Another study among Swiss children suggested that self-reported mobile phone call duration was associated with a decrease in difficulties. However, this relationship was not seen with operator-recorded mobile phone call duration (Roser et al., 2016). Regarding the protective effect at low dose, we may assume the J-shaped pattern between mobile phone call duration (using mobile network and internet) and change in total difficulties; those who used less than 5 minutes had higher odds of improvement (protective effect) and moderate internet calls (10 – 40 min/week) had lower odds of persistence in total difficulties (protective effect) while longer duration of internet calls had higher odds for concurrent total difficulties compared to non-users. In another study from the Danish National Birth Cohort (DNBC) conducted at seven years of age without behavioral difficulties at baseline, which showed an association between mobile phone calls and higher odds of total difficulties at 11 years of age (Sudan et al., 2016). Given the inconsistent association between indoor RF-EMF exposure sources and device usage pattern, these findings possibly unlikely related to RF-EMF exposure rather involves non-biophysical mechanism. These mechanisms can be explained by the higher cost of mobile network calls, parental control, easy access to the internet, and late-night internet calls that can themselves lead to problematic behavior (Sahu et al., 2019). Another possible explanation can be the impact of COVID-19, which increased the reliance on the digital communication, remote schooling, screen time behavior, and mental wellness of children, which possibly affected the exposure measurement in our study.

We examined mobile phone use not only for calling but also for playing online games, online audio streaming, and online video streaming as marginally related to RF-EMF. In previous studies, the use of mobile phones for texting, gaming, and social media has been associated with behavioral problems and depression (Primack et al., 2021; Zheng et al., 2014). However, these studies did not differentiate between the problematic use of mobile phones and mobile phone use related to RF-EMF exposure. In our study, we found an association between online audio streaming for 60–120 minutes per week and lower odds of persistent total difficulties. One can speculate, this may be because mobile phone use is a tool for relaxation (De-Sola De-Sola Gutiérrez et al., 2016). We need to consider that the use of mobile devices for audio streaming itself may not directly emit RF-EMF radiation such as mobile phone calls, and the process of accessing data via cellular networks or Wi-Fi connections involves transmission; therefore, these findings are suggestive of the device use for audio streaming, which itself can alleviate total difficulties (Harney et al., 2023).

The association between the presence of a cordless phone at home and higher odds of improvement in total difficulty scores can be explained by the confounding effects of family structure and home-rearing environment (Chen et al., 2016; Ruchkin et al., 2000). Children with a cordless phone call duration of more than 4 min per week were less likely to persist in problematic prosocial behavior. We can speculate that this is because interaction through the device leads to the development of social skills (Okada et al., 2021).

To our knowledge, this is the first study in Japan to investigate the change and persistence in behavioral problems and further exploring the effect of RF-EMF exposure markers on the change in behavioral problems using a longitudinal approach. As the first of its kind in this context, our research leverages data from birth cohorts, allowing us to review comprehensive information on participants since birth. Our detailed assessment of mobile phone usage pattern encompasses both RF-EMF related use and usage marginally related to RF-EMF. Additionally, we have gathered detailed information on usage durations, distinguishing between weekdays and weekends and then summing the results to determine complete usage duration in a week. This approach enhances the precision of our exposure assessment and the reliability of our findings, offering valuable insights into the complete nature of RF-EMF exposure and its potential impact on behavior problems in children.

Interpretation of the results should consider the limitations of our study. COVID-19 may have affected children's lifestyle and digital device usage, which could have affected the exposure measurement and change in behavior in our study. We did not have information on parental neuropsychiatric history, which can significantly impact behavioral outcome; this should be considered in future research. Further, we collected self-reported information on device usage; therefore, there is a chance of recall bias. Additionally, we did not observe cumulative cordless phone call duration or mobile phone use duration between baseline and follow-up which could be meaningful to further explain the change in behavior with the change in exposure. However, given the one-year follow-up nature of this study, we anticipate that the change in device use is not substantial. We cannot discard the possibility that our findings may be attributed to chance, given the extensive number of analyses conducted. Small sample size is another limitation, as for some exposures and outcome categories our sample was 5–6%; our sample had a wide range of ages, and age-specific associations are expected. The small sample size prevented us from completing age-specific stratification. Therefore, a larger sample should be analyzed. We acknowledge that presence or absence of RF-EMF sources and duration of cordless and mobile device usage are the proxies to RF-EMF, and these further depends on the network type, phone specifications, and distance to the head. However, previous research has shown mobile and cordless phones to be the main source of personal exposure to RF-EMF (Roser et al.,2015).

5. Conclusion

In this prospective study, we found sporadic associations between RF-EMF exposure markers and change and persistence in behavior problem. Although we assessed detailed RF-EMF exposure measures, future studies are needed to explore integrative RF-EMF exposure sources age-specific association with behavior problems. The inconsistent findings in our longitudinal analysis indicate the absence of causality rather the reverse causality in our cross-sectional results. The findings observed in our longitudinal analysis may be affected by confounding or chance findings, given the lack of a biophysical mechanism. Consequently, ongoing follow-up investigations are essential to better understand the association between RF-EMF sources and children's behavioral problems with evolving telecommunication devices as well as the increase in use with the advancement of age while controlling for confounding variables.

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Author Contributions

Ammara Ajmal conceptualized the study, synthesized the analysis plan, managed and analyzed the data, interpreted the findings, and wrote the manuscript. Keiko Yamazaki, Naomi Tamura, Yu Ait Bamai Atsuko Ikeda, and Toshio Yoshikawa were responsible for the study coordination, data collection, and subsequent revisions. Takashi Hikage revised the manuscript critically. Reiko Kishi was the principal investigator of the project and assisted in revising the manuscript. All the authors approved the final version of the manuscript.

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Appendix A. Supplementary materials

Supplementary materials associated with this manuscript can be found at xxx

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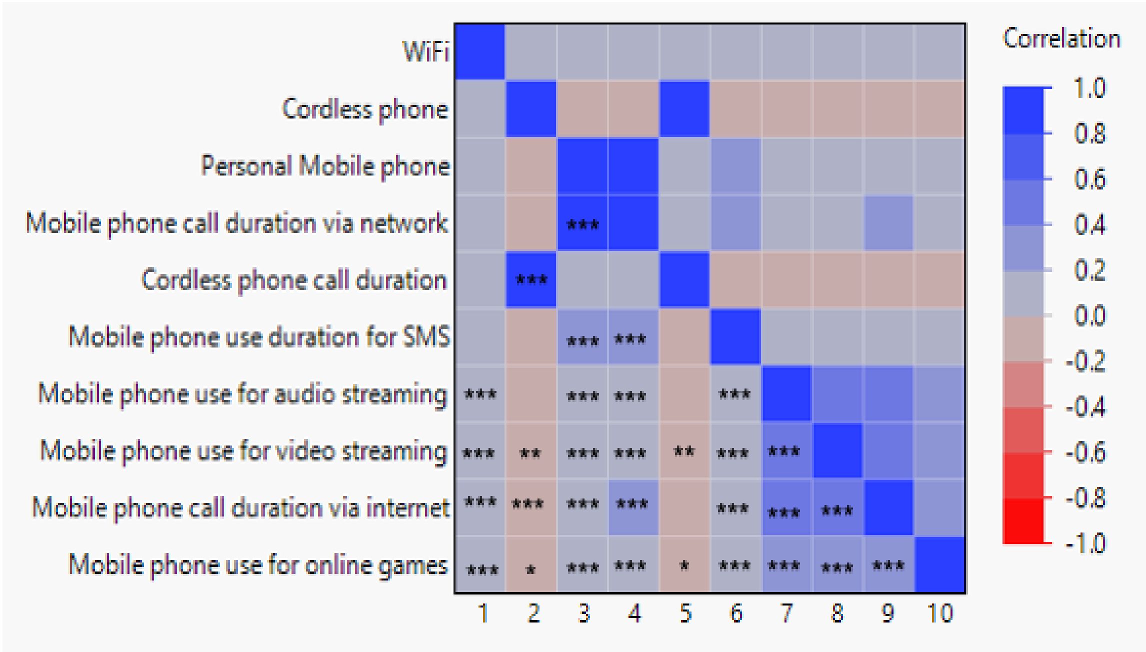
Figure 1. Correlation between exposure variables



Note: Along x-axis 1= WiFi, 2= Cordless phone, 3= Personal mobile phone, 4= Mobile phone call duration via network, 5= Cordless phone call duration, 6= Mobile phone use duration for SMS, 7= Mobile phone use for audio streaming, 8= Mobile phone use for video streaming, 9= mobile phone call duration via internet, 10 = mobile phone use for online games. * *p*-value <0.05, ***p*-value <0.01, ****p*-value <0.001