Prospective cohort analysis of cellphone use and emotional and behavioural difficulties in children

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ABSTRACT

Background We previously reported associations between cellphone exposure and emotional and behavioural difficulties in children in the Danish National Birth Cohort using cross-sectional data. To overcome the limitations of cross-sectional analysis, we re-examined these associations with prospectively collected data.
Methods Based on maternal reports, prenatal and postnatal cellphone exposures were assessed at age 7 years, and emotional and behavioural difficulties were assessed at 7 and 11 years with the Strengths and Difficulties Questionnaire. We used multivariable-adjusted logistic regression models to estimate ORs and 95% CIs relating prenatal exposure and age-7 cellphone use to emotional and behavioural difficulties at age 11 years.
Results Children without emotional and behavioural difficulties at age 7 years, but who had cellphone exposures, had increased odds of emotional and behavioural difficulties at age 11 years, with an OR of 1.58 (95% CI 1.34 to 1.86) for children with both prenatal and age-7 cellphone exposures, 1.41 (95% CI 1.20 to 1.66) for prenatal exposure only, and 1.36 (95% CI 1.14 to 1.63) for age-7 use only. These results did not materially change when early adopters were excluded, or when children with emotional and behavioural difficulties at age 7 years were included in the analysis.
Conclusions Our findings are consistent with patterns seen in earlier studies, and suggest that both prenatal and postnatal exposures may be associated with increased risks of emotional and behavioural difficulties in children.

INTRODUCTION

Between 2000 and 2014, the number of active cellphone subscriptions increased from 700 million to nearly 7 billion globally,[1 2] and cellphones are the highest localised source of common exposure to radiofrequency (RF) fields.[3 4] While no mechanism for an effect of RF from cellphones on human health has been confirmed, there remains concern about a possible effect on vulnerable populations such as children. WHO[5] and the National Academy of Sciences[6] have identified prospective cohort studies of RF exposure and neurological outcomes among children as a high-priority research need. Children may be at increased risk due to their still-developing organ and tissue systems, particularly the nervous system, and children have higher specific absorption rates of RF than adults.[7 8] Children born in the last 20 years have been exposed to cellphones starting in early life. They will likely continue to be exposed throughout their lives and reach a much higher lifetime exposure than seen before.

Studies among children and adolescents, including work by our group, found associations between cellphone use and changes in behaviour and cognitive function.[9–12] In our first study of 13 159 children in the Danish National Birth Cohort (DNBC), we found moderate associations between mothers' prenatal cellphone use and emotional and behavioural difficulties at age 7 years.[11] The strongest association was seen among children exposed both prenatally (mother used a cellphone while pregnant) and postnatally (child used a cellphone at age 7 years), with an OR of 1.80 and a 95% CI of 1.45 to 2.23 when compared with those with no exposure. The results also suggested a small positive association with postnatal-only use. To address possible confounding, we replicated these results in a separate group of 7-year-old children in the DNBC (n=28 745). The associations were weaker but remained after controlling for several additional confounders.[12] After excluding twins and triplets, the two data sets were combined and the results replicated in a group of 41 541 children, revealing consistent associations with enhanced statistical power. Further, these associations were not limited to early adopters of the technology. Our findings were supported by two smaller studies.[9 10] Investigators of another small study concluded that they did not find any association between prenatal cellphone use and emotional and behavioural difficulties in children, but their results were not inconsistent with our findings (CIs overlapped).[13 14]

In our previous investigations, emotional and behavioural difficulties were assessed at the same time as cellphone use, making recall bias or reverse causation potential explanations for bias. A new wave of data collection that assessed emotional and behavioural difficulties in children at age 11 years was recently completed in the DNBC. We re-examined the associations between cellphone use and emotional and behavioural difficulties among children at risk of behavioural problems with this new prospective data, overcoming the key limitation of our previous studies. Specifically, our current investigation examined associations of prenatal only, postnatal only, and both prenatal and postnatal cellphone exposures assessed at age 7 years with emotional and behavioural difficulties at age 11 years.

METHODS

The DNBC enrolled 91 661 pregnant women in Denmark during 1996–2002, with 9380 enrolled again during subsequent pregnancies within the enrolment period. Approximately 50% of all pregnant women in Denmark were invited to participate, and about 60% of those accepted. A total of

96 841 children were born into the cohort and have been followed since before birth. The DNBC collected detailed information on lifestyle and environmental exposures by computer-assisted telephone interviews with the women at gestational weeks 12 and 30, and again post partum when the children were 6 months and 18 months, and 7 years and 11 years old.[15] Information on social conditions, birth outcomes, and hospital diagnoses recorded in Denmark's national population registries is also linked to the DNBC. When children reached age 7 years, mothers completed self-administered questionnaires focusing on the child's health and development. Of the 91 256 mothers invited in the age-7 wave of data collection, 59 975 completed the questionnaire (66% participation rate). This investigation includes 54 908 singleton-born children whose mothers completed the age-7 questionnaire. When children reached age 11 years, a new wave of data collection was carried out. Age-11 data collection was completed in 2014, in which 47 721 mothers participated (52% of those invited).

Exposure

Exposure information was drawn from the age-7 DNBC questionnaire. Mothers responded to questions about their cellphone use during pregnancy as well as whether or not the child used a cellphone >1 h/week, <1 h/week, or not at all at age 7 years. Children whose mothers reported using a cellphone during pregnancy were classified as having prenatal exposure, and children who reportedly used a cellphone for any amount of time at age 7 years were classified as having postnatal exposure. Only a few children used a cellphone for >1 h/week, and thus, those who used a cellphone for more or <1 h/week were grouped into a single category for analysis. Prenatal and postnatal (age-7) cellphone exposure was grouped into 4 categories (0=no exposure, 1=prenatal exposure only, 2=age-7 use only, and 3=both prenatal exposure and age-7 use).

Outcomes

Outcome information was drawn from both the age-7 and age-11 questionnaires, in which emotional and behavioural difficulties were assessed using the parent version of the Strengths and Difficulties Questionnaire (SDQ), a validated standard tool for screening for behavioural problems in children.[16 17] Mothers responded to 25 statements regarding the child's behaviour on a three-point scale (1=not true, 2=partly true, and 3=very true). A previously developed algorithm generated a 'total difficulties' score using responses to 20 of the 25 items in the SDQ (http://www.sdqinfo.org). A priori-defined cut-off points were used to classify each child as 'normal' (score=0–13), 'borderline' (score=14–16), or 'abnormal' (score=17–40) for overall behavioural problems.[16] These cut-offs were based on population-based norms and are the same as cut-offs used in our previous studies.[12] The SDQ can also be used to assess difficulties on four individual subscales (conduct problems, emotional problems, peer problems and hyperactivity/inattention), but to remain consistent with previous DNBC publications, 'total emotional and behavioural difficulties at age 11 years was the main outcome of interest in this study. Information about emotional and behavioural difficulties at age 7 years was used to define subgroups in the analysis.

Statistical analysis

Our main analysis focused on the subgroup of children with 'normal' total emotional and behavioural difficulties scores at age 7 years (the cohort at risk) based on the SDQ, and followed this cohort prospectively to age 11 years. By excluding prevalent cases, we examined the change from a normal to an abnormal score as a function of cellphone use. To remain consistent with previous analyses, we used a three-level outcome variable (0=normal, 1=borderline, 2=abnormal) analysed using ordinal logistic regression models to compute ORs and 95% CIs for the associations of prenatal only, age-7 only, and both prenatal and age-7 cellphone exposure assessed at age 7 years with total emotional and behavioural difficulties at age 11 years. We tested the proportional odds assumption for each model in our analysis using the χ^2 score test for the proportional odds assumption. In each case, the proportional odds assumption was met according to the test as we were unable to reject the null hypothesis at $\alpha=0.05$. We adjusted for the child's sex, mother's age, mother's and father's history of psychiatric, cognitive, or behavioural problems as a child, socio-occupational status, gestational age at birth, mother's prenatal stress and breastfeeding. We chose these variables for adjustment to compare to the results of the second cross-sectional analysis by Divan et al.[12]

We also examined in more detail the associations between maternal phone use patterns during pregnancy and total emotional and behavioural difficulties at age 11 years in the cohort at risk. As in the previous analysis, the specific phone use characteristics examined were the number of times per day the mother spoke on her cellphone, the percentage of time her phone was powered on when not in use, and whether or not she used a hands-free device during pregnancy.

We performed a sensitivity analysis by repeating our main analysis in different subgroups. First, we conducted the analysis in the cohort of children at risk, but excluded those born prior to 1999 (early adopters). Second, we performed the analysis in all children with information on cellphone use at age 7 years regardless of their emotional and behavioural difficulties status at age 7 years.

All statistical models in our analysis were computed using complete-case analysis, and therefore, observations with missing values for the outcome, exposure, or other model covariates were dropped from the models. Since our adjusted models included several covariates with some missing values, we computed all unadjusted models two ways: (1) using the standard complete-case approach which dropped observations with missing values in the exposure or outcome variables; and (2) using an extended complete-case approach which dropped observations with missing values in the exposure, outcome, or any other variables included in the adjusted version of the model. Thus, the extended complete-case approach computed unadjusted models using the same sample as the adjusted models.

The Danish Data Protection Agency, the regional science ethics committees in Denmark, and the Office for the Protection of Research Subjects at the University of California, Los Angeles, all approved this study. Women in the DNBC gave written informed consent prior to inclusion in the cohort. Women who requested to discontinue participation at any time or whose child was deceased were not contacted for further follow-up.

RESULTS

Among the 51 190 children at risk of emotional and behavioural difficulties at age 7 years, 28 139 (55%) were exposed to cellphones, with 21% exposed prenatally only, 16% using cellphones postnatally at age 7 years only, and 19% exposed prenatally and postnatally at age 7 years. Approximately 41% were not exposed during either time period, and 4% were missing information about exposure (table 1). Of the children at

Table 1 Distributions of covariates and emotional and behavioural difficulties at age 11 years among children at risk of emotional and behavioural difficulties at age 7 years stratified by cellphone exposure categories (N=51 190)

	No exposure (n=20 801)	Prenatal exposure only (n=10 619)	Age-7 exposure only (n=7942)	Both prenatal and age-7 exposure (n=9578)	Unknown exposure (n=2250)
Sex					
Male	52.4	53.2	45.6	45.6	52.8
Female	47.6	46.8	54.4	54.4	47.2
Age of mother (in years)					
24 or younger	3.3	6.7	4.9	11.3	6.4
25–29	33.1	35.8	35.9	38.9	33.8
30–34	43.2	39.8	40.9	34.4	39.9
35–39	17.8	15.4	15.9	13.5	17.0
40 or older	2.5	2.3	2.3	2.0	2.8
Mother's history of psychiatric problems					
Yes	12.0	13.3	14.7	16.4	13.3
No	88.0	86.7	85.3	83.6	86.7
Socio-occupational levels					
High	73.1	72.1	69.9	64.8	66.5
Med	24.7	25.1	27.2	30.5	30.1
Low	2.2	2.8	2.9	4.7	3.4
Gestational age at birth (in weeks)					
<37 weeks	3.1	3.4	3.2	4.0	3.2
37–41 weeks	81.0	80.6	80.7	80.4	81.4
42 or greater	15.9	16.0	16.1	15.6	15.3
Mother's prenatal stress score					
Low (0–4)	93.6	93.1	91.7	90.4	91.0
Medium (5)	3.0	3.6	3.6	4.1	4.4
High (6–14)	3.4	3.3	4.7	5.6	4.6
Mother's history of psychiatric, cognitive, or behavioural problems as a child					
Yes	12.3	12.2	13.2	14.9	14.7
No	87.7	87.8	86.8	85.1	85.3
Father's history of psychiatric, cognitive, or behavioural problems as a child					
Yes	9.5	9.3	10.5	11.0	10.1
No	90.5	90.7	89.5	89.0	89.9
Child breastfed up to 6 months of age					
Yes	70.4	63.6	67.4	59.7	65.6
No	29.7	36.4	32.6	40.3	34.4
Total emotional and behavioural difficulties at age 11 years					
Normal	96.4	95.0	95.0	94.0	93.6
Borderline	2.1	2.9	2.8	3.6	3.9
Abnormal	1.5	2.1	2.2	2.4	2.5

Results are reported as percentages; missing values not shown.

risk whose mothers completed the Age-11 SDQ, 2% had an abnormal total emotional and behavioural difficulties score, 3% were borderline and 95% were normal.

When we examined our data with a cross-sectional analysis of cellphone exposure and emotional and behavioural difficulties at age 7 years, our results remained consistent with previous findings from Divan *et al* (not shown).

Among children at risk for emotional and behavioural difficulties at age 7 years, prenatal cellphone exposure and postnatal use at age 7 years were both associated with emotional and behavioural difficulties at age 11 years (table 2). Children with any use at age 7 years had 23% higher odds of emotional and behavioural difficulties than children without postnatal use, while any prenatal exposure was associated with 30% higher odds of the outcome. Although the CIs of the associations overlapped, the pattern in the results suggests that the association was strongest among children who were exposed both prenatally and used cellphones at age 7 years (OR: 1.58; 95% CI 1.34 to

1.86), followed by those with prenatal exposure only (OR: 1.41; 95% CI 1.20 to 1.66), and age-7 use only (OR: 1.36; 95% CI 1.14 to 1.63) compared with children with no exposure. The associations were present for each individual difficulties subscale and not driven by a single subscale, although they were slightly stronger for conduct problems (data not shown).

Among the 20 206 children whose mothers reported using a cellphone during pregnancy, specific maternal prenatal cellphone use patterns were not associated with emotional and behavioural difficulties in children at age 11 years (table 3). No clear 'exposure-response' trend was seen for frequency of use, percentage of time the phone was powered on, or use of a hands-free device in relation to emotional and behavioural difficulties at age 11 years. However, using a hands-free device 'often' was associated with higher odds of emotional and behavioural difficulties.

Repeating the main analysis in the cohort at risk while excluding early adopters, and again in all children including those with

Table 2 Associations between prenatal and age-7 cellphone exposure and total emotional and behavioural difficulties at age 11 years in children at risk of behavioural problems at age 7 years

	Unadjusted OR (95% CI) (n=32 913)	Unadjusted OR (95% CI) (n=24 499)*	Adjusted OR (95% CI)† (n=24 499)
Prenatal exposure			
No prenatal exposure‡	1.00	1.00	1.00
Prenatal exposure§	1.32 (1.19 to 1.47)	1.39 (1.23 to 1.58)	1.30 (1.15 to 1.48)
Postnatal exposure			
No age-7 exposure‡	1.00	1.00	1.00
Age-7 exposure¶	1.29 (1.16 to 1.44)	1.29 (1.14 to 1.47)	1.23 (1.09 to 1.40)
Prenatal and/or postnatal exposure			
No exposure‡	1.00	1.00	1.00
Prenatal only	1.40 (1.22 to 1.61)	1.48 (1.26 to 1.74)	1.41 (1.20 to 1.66)
Age-7 only	1.39 (1.19 to 1.61)	1.39 (1.17 to 1.66)	1.36 (1.14 to 1.63)
Both prenatal and age-7	1.69 (1.48 to 1.94)	1.78 (1.52 to 2.09)	1.58 (1.34 to 1.86)

n=48 940 with information about prenatal and age-7 exposure; n=49 014 with information about prenatal exposure; n=51 078 with information about age-7 exposure; only observations with non-missing values for all exposure, outcome, or covariates were included in the models.
*Sample used in model limited to observations included in adjusted model.
†Adjusted for sex of child, mother's age at birth, mother's and father's history of psychiatric, cognitive or behavioural problems as a child, combined socio-occupational status, gestational age, mother's prenatal stress and child breastfed up to 6 months of age.
‡Reference category.
§OR for prenatal exposure adjusted for age-7 exposure.
¶OR for age-7 exposure adjusted for prenatal exposure.

emotional and behavioural difficulties at age 7 years (table 4), did not change the associations much. The pattern in the results remained the same as in the analysis within only the cohort at risk (prospective analysis).

The results from the prospective analysis were also very similar to findings from the previous cross-sectional analysis from Divan *et al* (table 5). ORs for emotional and behavioural

difficulties at age 11 years were very similar to those at age 7 years among children with prenatal exposure only, or both prenatal exposure and age-7 use compared to those with no exposure. However, children who only had exposure at age 7 years had slightly higher odds of emotional and behavioural difficulties at age 11 years (OR: 1.4; 95% CI 1.1 to 1.6) than at age 7 years (OR: 1.2; 95% CI 1.0 to 1.3).

Table 3 Associations between mother's prenatal cellphone use patterns and total emotional and behavioural difficulties at age 11 years in children who had prenatal exposure and were at risk of emotional and behavioural difficulties at age 7 years (n=20 206)

	N (%)	Unadjusted OR	Unadjusted OR	Adjusted OR*
Times spoken per day		(n=11 844)	(n=8723)†	(n=8723)
0–1‡	10 189 (50.4)	1.00	1.00	1.00
2–3	5655 (28.0)	0.94 (0.78–1.13)	0.95 (0.77–1.17)	0.84 (0.68–1.05)
4+	2192 (10.9)	1.22 (0.95–1.56)	1.14 (0.84–1.54)	1.11 (0.82–1.52)
Missing	2170 (10.7)			
p for trend§		0.11	0.32	0.06
Percentage of time turned on		(n=13 049)	(n=9617)	(n=9617)
0‡	1349 (6.7)	1.00	1.00	1.00
<50	2342 (11.6)	1.17 (0.80–1.71)	1.32 (0.84–2.07)	1.24 (0.79–1.95)
50–99	6110 (30.2)	1.11 (0.79–1.56)	1.21 (0.80–1.82)	1.03 (0.68–1.56)
100	10 258 (50.8)	1.32 (0.95–1.82)	1.46 (0.98–2.16)	1.14 (0.77–1.71)
Missing	147 (0.7)			
p for trend§		0.49	0.44	0.39
Use of hands-free device		(n=13 072)	(n=9629)	(n=9629)
No‡	15 948 (78.9)	1.00	1.00	1.00
Rarely	2439 (12.1)	0.86 (0.67–1.11)	0.80 (0.60–1.08)	0.82 (0.60–1.11)
Often	1729 (8.6)	1.22 (0.95–1.56)	1.24 (0.92–1.67)	1.43 (1.06–1.92)
Missing	90 (0.5)			
p for trend§		0.07	0.04	0.02

Only observations with non-missing values for all exposure, outcome, or covariates were included in the models.
*Adjusted for sex of child, mother's age at birth, mother's and father's history of psychiatric, cognitive or behavioural problems as a child, combined socio-occupational status, gestational age, mother's prenatal stress, child breastfed up to 6 months of age and age-7 exposure to cellphones.
†Sample used in model limited to observations included in adjusted model.
‡Reference category.
§Test for deviation from linear trend.

Table 4 Sensitivity analysis of associations between prenatal and age-seven cell phone exposure and total emotional and behavioural difficulties at age 11 years

	Prenatal exposure only	Age-7 exposure only	Both prenatal and age-7 exposure
Cohort at risk*			
Unadjusted OR (n=32 913)	1.40 (1.22–1.61)	1.39 (1.19–1.61)	1.69 (1.48–1.94)
Unadjusted OR (n=24 499)†	1.48 (1.26–1.74)	1.39 (1.17–1.66)	1.78 (1.52–2.09)
Adjusted OR‡ (n=24 499)	1.41 (1.20–1.66)	1.36 (1.14–1.63)	1.58 (1.34–1.86)
Cohort at risk excluding early adopters§			
Unadjusted OR (n=29 359)	1.42 (1.23–1.64)	1.46 (1.24–1.72)	1.73 (1.50–2.00)
Unadjusted OR (n=22 731)†	1.47 (1.24–1.73)	1.42 (1.18–1.71)	1.78 (1.51–2.10)
Adjusted OR‡ (n=22 731)	1.39 (1.17–1.64)	1.38 (1.14–1.67)	1.55 (1.31–1.83)
All children¶			
Unadjusted OR (n=34 812)	1.48 (1.33–1.65)	1.33 (1.18–1.51)	1.85 (1.66–2.06)
Unadjusted OR (n=25 892)†	1.55 (1.36–1.76)	1.30 (1.12–1.50)	1.90 (1.68–2.16)
Adjusted OR‡ (n=25 892)	1.44 (1.26–1.64)	1.27 (1.09–1.47)	1.61 (1.42–1.84)

Reference category is no exposure.
Only observations with non-missing values for all exposure, outcome, or covariates were included in the models.
*All children with exposure information excluding those with emotional and behavioural difficulties at age 7 years: n=48 940.
†Sample used in model limited to observations included in adjusted model.
‡Adjusted for sex of child, mother's age at birth, mother's and father's history of psychiatric, cognitive or behavioural problems as a child, combined socio-occupational status, gestational age, mother's prenatal stress, child breastfed up to 6 months of age.
§All children with exposure information excluding those with emotional and behavioural difficulties at age 7 years and children born prior to 1999: n=42 776.
¶All children with exposure information: n=52 327.

DISCUSSION

We found that cellphone use at age 7 years was associated with emotional and behavioural difficulties in children at age 11 years. Prospectively collected data is a key strength of this investigation, as it overcomes limitations of previous cross-sectional studies. We do not expect our results to be due to reverse causation or recall bias, since we examined the development of emotional and behavioural difficulties over time in the subgroup of DNBC children who started with normal SDQ scores at age 7 years, and cellphone use was assessed 4 years prior to the outcome.

Findings from this cohort of at-risk children were consistent with those from our previous cross-sectional analyses. The

Table 5 Comparison of analysis using cross-sectional data from Divan et al, 2012 with analysis using current prospective data

	Prenatal exposure only	Age-7 exposure only	Both prenatal and age-7 exposure
Cross-sectional analysis*			
Unadjusted OR	1.5 (1.3–1.7)†	1.2 (1.1–1.4)†	2.0 (1.7–2.1)†
Adjusted OR‡	1.4 (1.2–1.5)	1.2 (1.0–1.3)	1.5 (1.4–1.7)
Prospective analysis§			
Unadjusted OR	1.4 (1.2–1.6)	1.4 (1.2–1.6)	1.7 (1.5–1.9)
Adjusted OR‡	1.4 (1.2–1.7)	1.4 (1.1–1.6)	1.6 (1.3–1.9)

Reference category is no exposure.
Only observations with non-missing values for all exposure, outcome, or covariates were included in the models.
*Results from Divan et al,[12] n=41 541; 'Cross-sectional analysis' of association between cellphone exposure assessed at age 7 years, and emotional and behavioural difficulties assessed at age 7 years; exact numbers of observations included in models are unknown.
†Confidence intervals were recalculated for this analysis because they were not given in the original publication by Divan et al.[12]
‡Adjusted for sex of child, mother's age at birth, mother's and father's history of psychiatric, cognitive or behavioural problems as a child, combined socio-occupational status, gestational age, mother's prenatal stress, child breastfed up to 6 months of age.
§All children with exposure information excluding those with emotional and behavioural difficulties at age 7 years: n=48 940; 'prospective analysis' using cellphone exposure assessed at age 7 years, and emotional and behavioural difficulties assessed at age 11 years.

highest odds of emotional and behavioural difficulties were seen among children with both prenatal and postnatal exposures, followed by those with prenatal exposure only, and those with postnatal exposure only. However, children with postnatal use only had higher odds of emotional and behavioural difficulties at age 11 years (OR: 1.4; 95% CI 1.1 to 1.6) than at age 7 years in the previous data set (OR: 1.2; 95% CI 1.0 to 1.3), although the CIs overlapped. No exposure-response trends were seen between maternal prenatal cellphone use patterns and emotional and behavioural difficulties at age 11 years, although using a hands-free device 'often' increased the risk estimate, consistent with higher exposure to the fetus which would occur if the phone were held or carried near the pregnant woman's abdomen.

Our results did not change materially after excluding early adopters from the cohort at risk, nor when including all children (including those with emotional and behavioural difficulties at age 7 years). Our findings suggest that both prenatal exposure and postnatal use increase the risk of emotional and behavioural difficulties in children, but as the length of time since the prenatal period increases, the impact of prenatal exposure on these difficulties decreases, while the role of postnatal use increases.

The DNBC is a large and well-documented birth cohort, and we used many sources of data on potential confounders, including prenatal and early life interviews and national Danish social and medical registers. By adjusting for the same potential confounders as in the previous investigation, we replicated the previous models using prospective data. For additional uncontrolled confounding to explain our results, there must exist a strong unmeasured confounder that is closely related to both cellphone use and emotional and behavioural difficulties. By computing our unadjusted models using both the standard complete-case approach and an extended complete-case approach, we accounted for differences between the unadjusted and adjusted models that may have been due to differences in the analytic samples. We found that the overall interpretation of the results did not materially change between the different approaches.

About 33% of children for whom cellphone use was assessed at age 7 years were missing information about emotional and behavioural difficulties at age 11 years, with slightly more missing data among those with both prenatal and postnatal cellphone exposure. This was mostly due to loss to follow-up. Previous research found that DNBC women who were lost to follow-up in earlier waves of data collection were more likely to be in the low socio-occupational status category than those who continued participation.[18] Some studies reported that socio-occupational status was inversely associated with cellphone use among children and adolescents.[19–22] Therefore, children (and possibly mothers) who were heavier cellphone users may have been less likely to continue follow-up and may be underrepresented in our data. The magnitude and direction of potential bias need to be evaluated further, but we do not expect such bias to account for all the consistent associations we observed.

Although prenatal cellphone exposure was assessed retrospectively, research suggests that pregnancy leaves a strong impression on women's memories, and they tend to remember their behaviours during this unique time with high accuracy.[23 24] We expect mothers to have been able to accurately recall whether or not they used a cellphone while pregnant, but we recognise that recall of specific cellphone use patterns may have been less accurate. However, our results relating maternal prenatal cellphone use patterns to emotional and behavioural difficulties at age 11 years were consistent with our previous results for emotional and behavioural difficulties at age 7 years.

Our findings support links between cellphone use and emotional and behavioural difficulties in children, and if they reflect causal effect, a number of mechanisms are possible. One possibility is that RF exposure from cellphones is a cause through an unidentified biological mechanism. The low level of RF exposure from cellphones, particularly to the fetus, argues against this. On the other hand, the association between prenatal exposure and emotional and behavioural difficulties is not confounded by many other aspects of cellphone use such as exposure to blue light from the screen or being woken at night by the phone. A second possibility is that cellphone use itself (not RF) leads to altered social development and changes in behaviour. Heavy media multitaskers may be more susceptible to distraction and have difficulty filtering out irrelevant environmental stimuli,[25] and certain cellphone activities have been linked to lower academic performance and higher levels of anxiety.[26] Altered brain function in children and adolescents in response to heavy cellphone use is not surprising, as neural plasticity is very high in these age groups. However, it is not clear to what extent cellphone use results in normal brain adaptation to new stimuli versus abnormal developmental processes, as this is likely to depend on the specific context and age of the child.[27] A third possibility is that the associations we detected reflect differences in parenting styles between heavy cellphone users and light users or non-users. However, parenting style is unlikely to fully explain our results, since children's postnatal cellphone use was associated with emotional and behavioural difficulties regardless of mothers' use.

With the popularity of smartphones, increasing numbers of children will be sending emails and text messages, while often simultaneously playing games, browsing the internet, and performing other activities on their devices. Heavy engagement in these activities could be harmful and may explain the associations with emotional and behavioural difficulties we observed. More research is needed to understand the effects of this technology in children. We will continue to examine these issues in our data with other analytic methods including bias analysis.[28 29]

New studies among children with prospective data collection should be conducted to corroborate our findings and to examine behaviour, cognition and cellphone exposure in more detail, and research should carry on into adulthood to continue to examine the potential effects of lifelong exposure.

What is already known on this subject?

Children are increasingly exposed to cellphones beginning at very early ages, including in utero. Many parents and paediatricians are concerned that this technology could have negative health effects, but studies of children's exposure are few.

What this study adds?

This is the first large-scale cohort study to prospectively examine cellphone use (during pregnancy and at age 7 years), and emotional and behavioural difficulties (at age 11 years). Our findings support a modest, but consistent, link between cellphone use and emotional and behavioural difficulties in children.

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