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Indoor air pollution exposure and early childhood development in the Upstate KIDS Study

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Abstract

Background: Limited human studies have investigated the impact of indoor air pollution on early childhood neurodevelopment among the US population. We aimed to examine the associations between prenatal and postnatal indoor air pollution exposure and early childhood development in a population-based birth cohort.

Methods: This analysis included 4735 mother-child pairs enrolled between 2008 and 2010 in the Upstate KIDS Study. Indoor air pollution exposure from cooking fuels, heating fuels, and passive smoke during pregnancy, and at 12 and 36 months after birth were assessed by questionnaires. Five domains of child development were assessed by the Ages and Stages Questionnaire at 4, 8, 12, 18, 24, 30, and 36 months. Generalized estimating equations were used to estimate odds ratios (ORs) and 95% confidence intervals (CIs), adjusting for potential confounders.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2023.116528.

Results: Exposure to unclean cooking fuels (natural gas, propane, or wood) throughout the study period was associated with increased odds of failing any development domain (OR = 1.28, 95% CI 1.07, 1.53), the gross motor domain (OR = 1.52, 95% CI: 1.09, 2.13), and the personal-social domain (OR = 1.36, 95% CI: 1.00, 1.85), respectively. Passive smoke exposure throughout the study period increased the odds of failing the problem-solving domain by 71% (OR = 1.71, 95% CI 1.01, 2.91) among children of non-smoking mothers. No association was found between heating fuel use and failing any or specific domains.

Conclusion: Unclean cooking fuel use and passive smoke exposure during pregnancy and early life were associated with developmental delays in this large prospective birth cohort.

Keywords

Indoor air pollution; Cooking fuels; Heating fuels; Passive smoke; Child development; Longitudinal

1. Introduction

Indoor air pollution is a key contributor to the global burden of disease. Indoor air pollutants comprise a complex mixture of particulate matter (PM), carbon monoxide (CO), polycyclic aromatic hydrocarbons (PAHs), nitrogen dioxide (NO_2), and various organic compounds. Burning wood for heating is an important source of indoor PM in many developed countries, particularly in rural settings. In the US, nearly 13 million homes use wood as a primary or secondary heating source (US Energy Information Administration, 2015), and 80% of wood stoves are old and inefficient, producing $PM_{2.5}$ levels indoors that exceed health-based standards (Air Quality Management Work Group, 2005). In homes that use solid fuels for cooking and heating, 24-h mean indoor $PM_{2.5}$ and PM_{10} are much higher than the WHO guideline for outdoors ($PM_{2.5}$: 25 μ/m^3 and PM_{10}: 50 μ/m^3) (Hadeed et al., 2021; Robin et al., 1996; WHO, 2014). Gas stoves are a main contributor to indoor CO and NO_2, and homes with gas appliances can lead CO and NO_2 levels twice as high as homes without gas stoves (Chauhan, 1999; Levy, 2015). Passive smoke is also a significant source of indoor air pollution. About 40% of children, 35% of women, and 33% of men are exposed to passive smoking in their daily lives (Oberg et al., 2011).

Growing evidence indicates that air pollutant exposure during early life may play a role in neurodevelopmental toxicity, either directly by transport of nanosized particles into the central nervous system (CNS) or indirectly through systemic inflammation, oxidative stress, and DNA damage (Block et al., 2012; Grahame et al., 2014; Peters et al., 2006). Prenatal and postnatal exposures to specific ambient air pollutants, such as PM, NO_2, and CO, have been linked to children's neurodevelopment (Basagana et al., 2016; Dix-Cooper et al., 2012; Kim et al., 2014; Lin et al., 2021; Loftus et al., 2020; Perera et al., 2012; Peterson et al., 2015; Yorifuji et al. 2016, 2017). In fact, an analysis of prenatal ambient $PM_{2.5}$ in the current cohort identified such an association (Ha et al., 2019). Nevertheless, indoor air pollution exposure has not been well studied. To date, much of the research on indoor air pollution exposure from unclean cooking and heating fuels and neurodevelopmental delays among children has been conducted in lower- and middle-income countries (Brabhukumr et al., 2020; Christensen et al., 2022; Fang et al., 2020; Nazif-Muñoz et al., 2020; Sathiakumar

et al., 2019; Yang et al., 2022). In addition, although many studies have indicated the positive association of prenatal passive smoke exposure with early developmental delays (Chen et al., 2013; Jedrychowski et al., 2010; Julvez et al., 2021; Lee et al. 2011, 2019), few have evaluated the longitudinal effect of passive smoke exposure from prenatal to postnatal period (Mohamed et al., 2018; Wei et al., 2021). While the fetus may be particularly vulnerable to exposures because of rapid cell growth and differentiation, immature metabolic systems, and developing vital organ systems (Sunyer, 2008); after birth, infants and young children are also vulnerable because their organs and systems have not been fully developed, and they spent more time indoors (Bearer, 1995; Vrijheid, 2014; Weitzman et al., 2013). To our knowledge, none of the studies in the US has investigated the role of longitudinal exposure to indoor air pollution due to unclean fuels and passive smoke from prenatal to early-life periods in child developmental milestones.

Certain infants may also be more susceptible to the impact of indoor air pollution on neurodevelopment. Maternal cigarette smoking and advanced maternal age are associated with poor neuropsychological outcomes (Knopik et al., 2012; Sandin et al., 2012). Compared with singletons, twins are considered to be at an increased risk for neurodevelopmental impairments (Figueras et al., 2021; Lorenz, 2012). In addition, mothers with multiple pregnancies, advanced age, and who smoke are more likely to have higher levels of oxidative stress (Chełchowska et al., 2018; Jantsch et al., 2020; Odame Anto et al., 2018) and thus may respond differently to indoor air pollution compared to those who delivered singletons, who are younger, and non-smokers.

In this study, we aimed to examine the associations of indoor air pollution exposures from cooking fuels, heating fuels, or passive smoke during pregnancy and early life, with early childhood development up to three years in a large prospective US birth cohort. Furthermore, we aimed to explore if the associations would differ by subgroups (i.e., smoking status, maternal age, plurality, and infant sex).

2. Materials and methods

2.1. Study design and population

The Upstate KIDS Study is a population-based birth cohort (Buck Louis et al., 2014). The study initially focused on examining the association between infertility treatment and child development (Yeung et al., 2016). The referent population comprises resident mothers who delivered live births in Upstate New York (57 counties excluding 5 New York City boroughs) between July 2008 and May 2010 (Buck Louis et al., 2014). All mothers of singletons whose birth certificates noted the use of infertility treatment were invited to participate in the study approximately 2–4 months after delivery. They were frequency-matched to mothers of singletons without infertility treatment on the maternal geographic residence of birth at a 1:3 ratio (Buck Louis et al., 2014). Mothers of multiples (twins and higher order) were also invited to participate regardless of treatment. In total, 5034 mothers (27.2% of 18 479 approached) and 6171 children were recruited (Buck Louis et al., 2014). Study participants were interviewed at baseline (at 4 months) and followed up at 8, 12, 18, 24, 30, and 36 months of age (Buck Louis et al., 2014). Parents provided written informed consent prior to data collection. We randomly selected one child per household

and excluded those with missing cooking and heating fuel exposures at baseline. Then, we included those with at least one developmental score throughout the study period, resulting in 4735 mother-child pairs (Fig. 1). The New York State Department of Health and the University at Albany (State University of New York) Institutional Review Boards approved this study, along with a signed reliance agreement with the National Institutes of Health. All participants provided written informed consent.

2.2. Exposure assessment

Indoor air pollution exposure was assessed by collecting information on cooking fuels, heating fuels, and passive smoking at baseline (at approximately 4 months old), at 12 months, and at 36 months (Fig. S1). In the baseline questionnaire, mothers were asked about their exposures during pregnancy postnatally (4m after birth). Specifically, they were asked, during this pregnancy, what fuel was usually used for cooking (natural gas, wood, propane, electricity, or microwave) and heating (electricity, natural gas heating system, wood burning stove, pellet stove, wood fireplace, gas fireplace, coal, kerosene, paraffin, propane, corn, oil, or solar), and if they lived with a smoker (yes or no).

The 12-month questionnaire asked mothers what fuel source was usually used for cooking since the birth of the child, and how many times per month it was used (choose one or more from natural gas, propane, wood, or electricity). The question addressing heating fuel was asked the same way as the baseline questionnaire, however, participants could select more than one fuel type. For passive smoking, participants were asked since the birth of their child, did others smoke in the same room at home or in the car with the child (no or yes). The 36-month questionnaire assessed exposures that occurred in the past year (24–36 months), and indoor air pollution (cooking fuel, heating fuel, and passive smoking) was addressed in the same way as the 12-month questionnaire.

In the present study, participants with clean fuel use were those who only used electricity (including microwave) for cooking and used electricity or solar for heating, while unclean fuel users included those who used one or more fuels other than electricity.

2.3. Outcome assessment

Child development was measured by the Ages and Stages Questionnaire© (ASQ), a validated parental rating instrument used for screening children's development and milestone achievement (Schonhaut et al., 2013). The ASQ second edition (Squires et al., 1995) was used for screening at ages 4–12 months, and the third edition was used from ages 18 months onwards as it was released in 2009 (Squires et al., 2009). Parents were encouraged to perform required activities with their children at 4, 8, 12, 18, 24, 30, and 36 months of age (corrected for gestation) to accurately respond to ASQ capturing 5 developmental domains: communication, gross and fine motor, personal-social, and problem-solving. Parents were asked to indicate whether their child can do the activity all the time, sometimes, or not yet, with each response converted into a point value (yes = 10, sometimes = 5, and not yet = 0). Scores are totaled for each of the five developmental areas, ranging from 0 to 60 (Squires et al. 1995, 2009). Domain-specific fail is defined as 2 standard deviations below the U.S. national normed mean for the child's age (Squires

et al. 1995, 2009). Parents were contacted by study personnel when the child failed any of the 5 domains, or parental concern was noted (Yeung et al., 2016). Trained specialists implemented an age-appropriate follow-up ASQ for the failed domain(s) (Yeung et al., 2016). The child was considered to have failed the domain if also failing the follow-up screen or if the parent was not reachable. Age at failure was defined as the time of the initial screen failure regardless of the time of the follow-up. Screening instruments were considered valid only if completed in the specified age windows (Squires et al. 1995, 2009). The present study included children with at least one developmental score at 4, 8, 12, 18, 24, 30, or 36 months. Missing responses in specific domains were imputed as no fail in that domain. “Any fail” was defined as if the child failed any of the 5 domains of ASQ, while “No fail” was defined as if the child did not fail in any domains.

2.4. Covariates assessment

The maternal baseline questionnaire captured information about the medical and reproductive history, behaviors while pregnant (alcohol consumption, smoking), and sociodemographic characteristics (such as maternal and paternal age, marital status, race and ethnicity, and education). The baseline questionnaire also collected newborn characteristics, including feeding practices and health status. Certain characteristics (such as maternal and paternal age, insurance status, gestational age, birth weight, pre-pregnancy body mass index [BMI], infant sex, plurality, and delivery method) were retrieved from vital records.

2.5. Statistical analysis

Means and standard deviations were calculated for continuous variables, and percentages were calculated for categorical variables. Characteristics at baseline were compared by cooking fuels, heating fuels, and passive smoking using chi-square tests, and by developmental outcomes using analysis of variance (ANOVA).

Directed acyclic graphs (DAGs) were created to determine possible confounders and minimally sufficient adjustment sets (Fig. S2 and Fig. S3). For parsimony, selected variables were added to the crude model to evaluate whether there was a 10% or more change in the beta estimate to determine the covariates in the final models. Birth weight, gestational age, and any childcare at 4 months were dropped as covariates. For cooking and heating fuel, final models adjusted for maternal age (continuous), maternal race/ethnicity (non-Hispanic White, other), maternal education (HS or below, above HS), paternal education (HS or below, above HS), insurance status (private insurance, otherwise), pre-pregnancy BMI (continuous), marital status (married, otherwise), plurality (singleton, non-singleton), active smoking during pregnancy (no, yes), and passive smoking during pregnancy (no, yes). The same covariates were included for passive smoking.

Generalized estimating equations (GEE) with a logit link were used to estimate adjusted odds ratios (aORs) and 95% confidence intervals (CIs) of failing any or specific ASQ domains in association with each indoor air pollution exposure. Infant-level random intercepts were included to account for repeated measures of infants, and sampling weights were applied to account for oversampling infants conceived with infertility treatment and twins in the study design (Buck Louis et al., 2014). Weights were derived using New York

State birth certificate data on infertility treatment, plurality, and region of birth. Cooking fuels and heating fuels were categorized as clean fuel use (i.e., electricity; referent group) and unclean fuel use (i.e., all other fuel types). Passive smoking was classified as exposed and unexposed (referent) groups. Time was modeled using the seven categorical time points that were available (at 4, 8, 12, 18, 24, 30, and 36 months). Since exposure measurements were only collected at three-time points (at baseline [4 months], 12, and 36 months), assumptions were made for the other four time points. Exposure at 12 months was assumed to be the same for 8, 18, and 24 months, while exposure at 36 months was assumed to be the same for 30 months. Stratified analyses were conducted by smoking status (smokers and non-smokers), plurality (singletons and non-singleton), maternal age (<35 and ≥ 35 years), and infant sex (male, female). A product term of exposure and the covariate of interest was added to the model, and the significance of the interaction was tested. False discovery rate (FDR) was used to adjust for multiple comparisons.

All statistical analyses were conducted with SAS 9.4 (Cary, NC). A p-value <0.05 was considered statistically significant.

3. Results

3.1. Study population characteristics

As shown in Table 1, at baseline, 9.1% of children failed at least one of the ASQ developmental domains, while domain-specific fails were fewer, ranging from 1.8 to 3.7%. Those who failed at least one domain were more likely to be born from older mothers, with a lower birth weight, smaller gestational weeks at birth, non-singletons, and Cesarean birth. Tables S1–S3 present the differences in baseline characteristics by type of cooking fuels, heating fuels, and passive smoke exposure at used electricity or natural gas as cooking fuels (Tables S1). With regards baseline, respectively. Mothers who used propane/wood cooking fuel to sources of heating fuels, solid fuels were more likely to be used among (9%) tended to be younger, non-Hispanic White, have lower education, non-Hispanic White and married mothers compared to all other fuels have higher pre-pregnancy BMI, and smoke, compared to those who (Table S2). Non-smokers who reported being exposed to passive smoke were more likely to be younger, have lower education, and less likely to be married and have private insurance than other non-smokers (Table S3).

3.2. Indoor air pollution exposure and child development

In the longitudinal analysis of all ASQ data from 4 to 36 months (Table 2), unclean cooking fuel exposure (i.e., grouping propane/wood and gas v. s. electricity) increased the odds of failing any developmental domain by 28% (aOR = 1.28, 95% CI: 1.07, 1.53), the gross motor domain by 52% (aOR = 1.52, 95% CI: 1.09, 2.13), and the personal-social domain by 36% (aOR = 1.36, 95% CI: 1.00, 1.85). No associations were present for unclean heating fuels (i.e., grouping gaseous, liquid, and solid fuels v. s. electricity/solar) or passive smoke exposure (yes v. s. no) and failing any or specific developmental domains in the overall population.

3.3. Stratified analysis

When restricted to infants of mothers who did not smoke during pregnancy, we observed positive associations of unclean cooking fuel exposure with failing any domain (aOR = 1.32, 95% CI: 1.08, 1.61) and gross motor domain (aOR = 1.70, 95% CI: 1.16, 2.48), and passive smoke with failing the problem-solving domain (aOR = 1.71, 95% CI: 1.01, 2.91) among their children, while the associations were not significant among smokers (cooking fuel exposure and any domain: aOR = 1.12, 95% CI: 0.73, 1.71; cooking fuel exposure and gross motor domain: aOR = 0.94, 95% CI: 0.43, 2.03; passive smoke and problem-solving domain: aOR = 0.59, 95% CI: 0.28, 1.26). We observed significant associations of unclean cooking with failing any domains and specific domains among infants of young mothers, singletons, and male infants, but not among infants of older mothers, non-singletons, or female infants. We did not observe any significant interactions after multiple comparisons (all *P*-for-interaction >0.05) (Table S4).

4. Discussion

In this prospective, population-based birth cohort of 4735 mother-child pairs, we found unclean cooking fuel exposure (natural gas, propane, or wood) throughout the study period was associated with failing a screening instrument on any developmental domain, the gross motor domain, and the personal-social domain. Passive smoke exposure among non-smokers throughout the study period was associated with failing the problem-solving domain.

The combustion of unclean fuels generates many air pollutants, including PM, NO_2, CO, and PAH, many of which are responsible for neuropsychological damage (Payne-Sturges et al., 2019). Inhaled pollutants deposited in the respiratory tract can translocate to the CNS via the nasal olfactory mucosa or the blood-brain barrier (Block et al., 2012; Elder et al., 2006), resulting in oxidative stress, neuroinflammation, persistent microglia activation, DNA damage, and white matter injury in the brain (Allen et al., 2014; Block et al., 2012; Calderon-Garciduenas et al., 2003; Levesque et al., 2011). In addition, air pollutants may exert systemic effects through circulating inflammatory cytokines, following an initial local response in the respiratory tract, resulting in inflammation and oxidative stress damage in other organs, including the brain (Calderón-Garcidueñas et al., 2007; Costa et al., 2014). Among pregnant women, pollutant-induced oxidative stress and inflammation could alter the placenta function and compromise the mother-fetus interaction, impairing embryo development (Veras et al., 2008) and disrupting fetal neurodevelopmental processes (Saenen et al., 2015). In addition, some pollutants can cross the placental barrier (Wick et al., 2010), leading to fetal hypoxia and affecting child brain development (Lee et al., 2011; Weitzman et al., 2002). Emerging evidence from animal studies indicates that air pollution exposure during the gestational period may alter spatial learning and memory, neurotransmitter levels, and spontaneous locomotor activity in the offspring (Bolton et al., 2012; Ehsanifar et al., 2019; Gonzalez-Pina et al., 2008; Suzuki et al., 2010).

Our findings are consistent with previous epidemiological studies that unclean cooking fuel use is associated with delayed children neurodevelopment, specifically in gross motor, communication, and personal-social domains. A cross-sectional study in Ghana found that children aged 3–5 years exposed to solid fuel use were more likely to have development

delays in socio-emotional development and learning-cognition (Nazif-Muñoz et al., 2020). Gas cooking was related to a 2.5-point decrease (95% CI: 4.0, −0.9) in mental development scores compared to non-gas cookers in a prospective birth cohort study of 1887 children aged 11–22 months in Spain (Vrijheid et al., 2012). Although there is limited research on the effect of indoor air pollutants, many studies indicate that ambient air pollutants are associated with children neurodevelopment. Exposure to ambient PM_{10} and NO_2 during pregnancy posed a significant adverse effect on the child's mental and psychomotor developmental index (Guxens et al., 2014; Kim et al., 2014). A birth cohort study of 533 mother-infant pairs found prenatal non-methane hydrocarbon (NMHC) levels negatively affected gross motor scores at six months of age, while exposure to sulfur dioxide during pregnancy and from birth to 12 months of age was adversely associated with fine motor scores at 18 months of age (Lin et al., 2014).

Many heating appliances rely on the combustion of carbon-based fuels, which could lead to potential sources of indoor air pollution, including CO_2, CO, and NO_2. The use of these devices (e.g., wood burning stoves, propane- or kerosene-fueled space heaters, and some gas-fueled log sets) in closed settings may be associated with the risk of exposure to the emissions. Therefore, we hypothesized that using unclean heating fuels (gaseous, liquid, and solid fuels) might increase the odds of developmental delays in any or specific domains. However, we did not observe any significant associations in our study. Using solid fuel for heating in the United States is not consistently considered to occur in poverty. It may also be used as an optional and supplemental source of heating fuels or simply for recreational use among middle- or high-income families (Rogalsky et al., 2014). In addition, participants who used electricity as the main source of heating fuel in our study tended to be with lower education levels and smokers, which are risk factors for adverse children neurodevelopmental outcomes (Koutra et al., 2012). Our null results could be potentially explained by residual confounding.

Prenatal and postnatal passive smoke exposure has been consistently associated with problems in child development (Herrmann et al., 2008). Passive smoke is composed of more than 4000 chemicals, such as nicotine, PAHs, aromatic amines, and CO, and many of these substances can cross the placenta and affect the developing embryo and fetus (Curtis et al., 2014; Saunders et al., 2012). These compounds could reduce utero-placental blood flow, result in fetal hypoxia, and affect fetal brain development (Lee et al., 2011). Other toxicants in the passive smoke, such as lead, could disturb the production of hemoglobin and therefore reduce oxygen to the brain and influence diverse processes critical for the CNS development of children (Lee et al., 2011; Mohamed et al., 2018). In our study, 21.5% of women reported exposure to passive smoke during pregnancy, and 14.2% reported to be active smokers during pregnancy. In this study, we observed a positive association of passive smoke exposure throughout the entire study with failing the problem-solving domain among children of non-smoking mothers. So far, our findings are consistent with previous studies, although few studies have measured all five developmental areas (fine and gross motor, communication, personal-social, and problem-solving). There is evidence that passive smoke is associated with delayed milestone achievement across gross motor (Evlampidou et al., 2015; Wei et al., 2021), fine motor (Hsieh et al., 2008; Mohamed et al., 2018; Wei et al., 2021), language-related domains (Hsieh et al., 2008; Mohamed et al.,

2018; Polanska et al., 2017; Wei et al., 2021), social-related domains (Wei et al., 2021), and problem-solving skills (Mohamed et al., 2018). Studies have also indicated that prenatal passive smoke exposure negatively impacts cognitive parameters among children (Chen et al., 2013; Eskenazi and Castorina, 1999; Lee et al., 2011). Our study found no association between passive smoke exposure and child development among mothers who were active smokers during pregnancy. These findings can be probably explained by the strong effect of active smoking. However, we cannot conclude that passive smoking has no or little additional effect on child development among active smokers during pregnancy. Passive smoke in the indoor environment contributes 14%–23% of benzo(a)pyrene exposure among active smokers, and thus the contribution of passive smoke may not be negligible and should be further studied (Piccardo et al., 2010).

This study has several strengths. The Upstate KIDS Study is a large prospective cohort study that recruited children from 4 months and followed them until 3 years old, which allows us to repeatedly assess indoor air pollution exposure from prenatal to 3 years after birth and to longitudinally assess the development of children for seven times using validated neuropsychological tests and questionnaires. However, several limitations of our study have to be acknowledged. First, the loss to follow-up at 36 months (about 54%) resulted in a lower power in association analysis. Those who completed the follow-up tended to be older, non-Hispanic White, married, have a higher education, and have private insurance (Table S5). Second, although validated and widely used, ASQ is a screening tool instead of a diagnostic instrument. There may be misclassification in the outcomes because children were considered to have failed the domain if their parents were unreachable for the follow-up screen. But this may be non-differential to the exposures because participants were not aware of the results of the ASQ screening when completing the questionnaires. Third, misclassification of exposure could not be ruled out because participants only chose one cooking or heating fuel type in the baseline questionnaire. Finally, due to the small number of cases, we were underpowered to examine the associations for specific fuel types. Additionally, a few of the associations achieved statistical significance by chance due to the limited number of cases and a large number of comparisons in our study.

5. Conclusion

To our knowledge, this is the first study to examine the impact of cooking fuels, heating fuels, and passive smoking on child development measured in five domains in the US. Overall, our study observed a positive association of unclean cooking fuel exposure with failing any, gross motor, communication, and personal-social developmental domains, and passive smoke exposure with developmental delay in problem-solving skills among children of non-active smokers during pregnancy. More studies with larger sample sizes are required to confirm our findings.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Data availability

Data will be made available on request.

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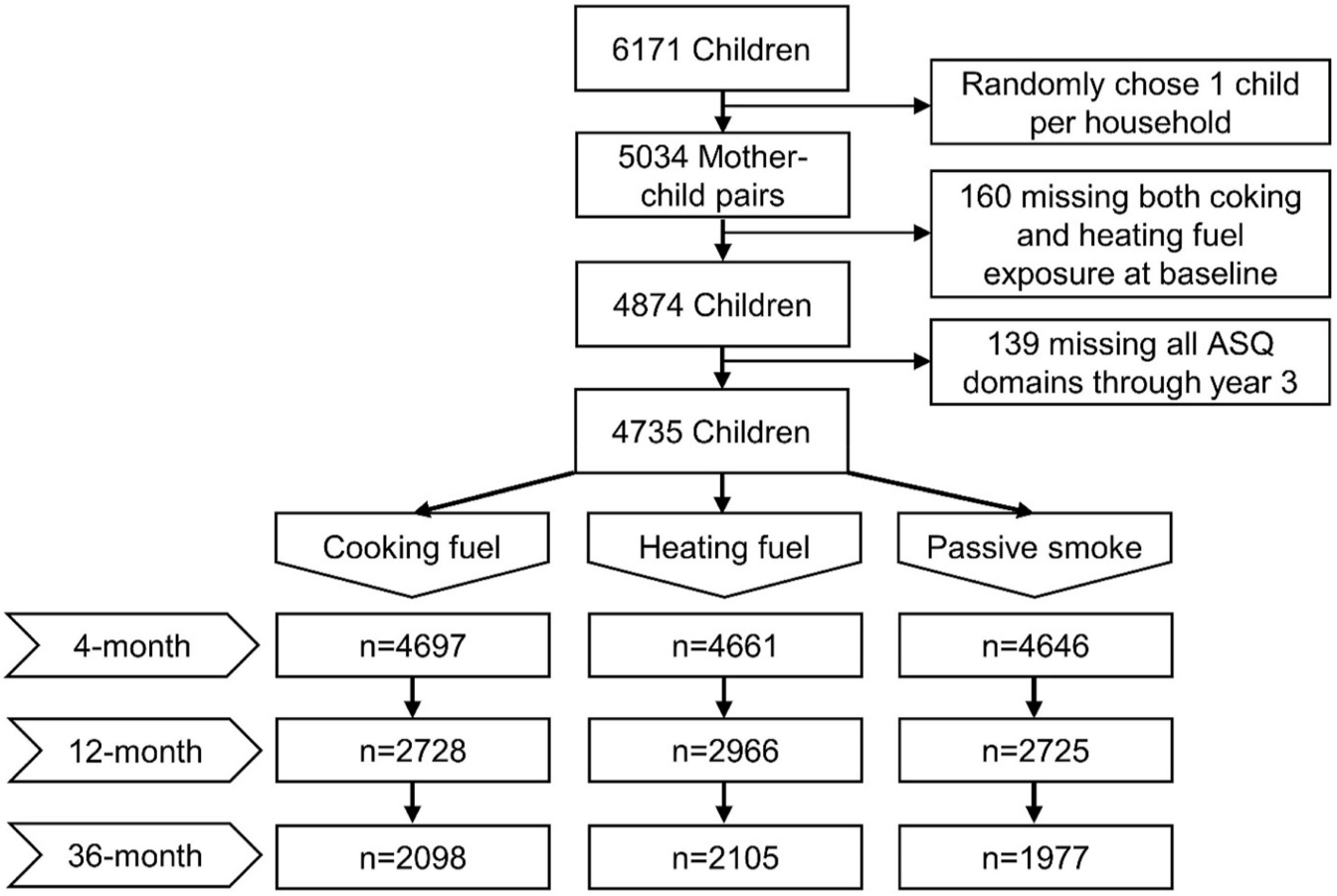

Fig. 1.
Flowchart of number of participants throughout the study period.

Table 1

Baseline characteristics of participants by fail status for any domain and specific domain in the ASQ screening at 4 months in the Upstate KIDS (n = 4244).

Baseline Characteristics	No fail	Any fail	Specific domain fail				
			Fine motor	Gross motor	Communication	Personal-social	Problem solving
Overall, N (%)	**3858 (90.9)**	**386 (9.1)**	**157 (3.7)**	**127 (3.0)**	**74 (1.8)**	**104 (2.5)**	**103 (2.5)**
Maternal age, mean ± SD	30.4 ± 6.0	31.3 ± 6.4 *	31.9 ± 6.0 *	31.3 ± 6.8	30.9 ± 5.7	32.0 ± 5.6 *	30.8 ± 6.6
Paternal age, mean ± SD	33.1 ± 6.7	33.8 ± 7.4	34.3 ± 7.9 *	33.9 ± 7.4	33.9 ± 6.5	33.6 ± 6.5	33.5 ± 7.4
Maternal race/ethnicity, n (%)							
Non-Hispanic White	3168 (82.1)	306 (79.3)	124 (79.0)	112 (80.0)	68 (81.0)	102 (82.9)	82 (75.9)
Non-Hispanic Black	163 (4.2)	19 (4.9)	8 (5.1)	8 (5.7)	5 (6.0)	5 (4.1)	7 (6.5)
Non-Hispanic Asian	95 (2.5)	15 (3.9)	5 (3.2)	3 (2.1)	1 (1.2)	4 (3.3)	6 (5.6)
Hispanic	331 (8.6)	35 (9.1)	15 (9.6)	12 (8.6)	6 (7.1)	11 (8.9)	10 (9.3)
Mixed or other	101 (2.6)	11 (2.8)	5 (3.2)	5 (3.6)	4 (4.8)	1 (0.8)	3 (2.8)
Maternal education, n (%)							
< HS	213 (5.5)	26 (6.7)	3 (1.9)	10 (7.1)	5 (6.0)	10 (8.1)	10 (9.3)
HS/GED equivalent	476 (12.3)	63 (16.3)	23 (14.6)	25 (17.9)	17 (20.2)	19 (15.4)	21 (19.4)
Some college	1176 (30.5)	102 (26.4)	46 (29.3)	33 (23.6)	19 (22.6)	28 (22.8)	30 (27.8)
College	848 (22.0)	84 (21.8)	37 (23.6)	34 (24.3)	21 (25.0)	23 (18.7)	23 (21.3)
Advanced degree	1145 (29.7)	111 (28.8)	48 (30.6)	38 (27.1)	22 (26.2)	43 (35.0)	24 (22.2)
Paternal education, n (%)							
< HS	319 (8.5)	37 (9.8)	14 (9.1)	12 (8.7) *	8 (9.9)	10 (8.3)	13 (12.4) *
HS/GED equivalent	727 (19.3)	91 (24.1)	34 (22.1)	44 (31.9) *	22 (27.2)	25 (20.8)	34 (32.4) *
Some college	754 (20.0)	75 (19.9)	28 (18.2)	26 (18.8) *	17 (21.0)	25 (20.8)	17 (16.2) *
College	1300 (34.4)	103 (27.3)	52 (33.8)	33 (23.9) *	20 (24.7)	38 (31.7)	25 (23.8) *
Advanced degree	675 (17.9)	71 (18.8)	26 (16.9)	23 (16.7) *	14 (17.3)	22 (18.3)	16 (15.2) *
Married, n (%)	3358 (88.2)	347 (91.1)	145 (94.2) *	124 (89.2)	77 (93.9)	108 (89.3)	92 (87.6)
Insurance, n (%)							
Private	2901 (75.3)	293 (75.9)	125 (79.6)	103 (73.6)	64 (76.2)	98 (79.7)	75 (69.4)
Otherwise [a]	954 (24.7)	93 (24.1)	32 (20.4)	37 (26.4)	20 (23.8)	25 (20.3)	33 (30.6)

Baseline Characteristics	No fail	Any fail	Specific domain fail				
			Fine motor	Gross motor	Communication	Personal-social	Problem solving
Pre-pregnancy BMI (kg/m^2), mean ± SD	27.1 ± 6.9	27.5 ± 6.9	28.4 ± 6.8 *	27.1 ± 6.5	27.8 ± 7.0	27.1 ± 6.9	28.3 ± 7.3
Paternal BMI (kg/m^2), mean ± SD	28.3 ± 5.4	28.2 ± 5.8	27.9 ± 5.5	27.5 ± 5.5	27.9 ± 5.6	28.3 ± 6.0	28.9 ± 6.4
Any alcohol during pregnancy, n (%)	491 (12.7)	47 (12.2)	20 (12.7)	18 (12.9)	9 (10.8)	10 (8.1)	7 (6.5)
Smoked during pregnancy, n (%)	541 (14.0)	53 (13.7)	14 (8.9)	22 (15.7)	13 (15.5)	15 (12.2)	14 (13.0)
Birth weight (g), mean ± SD	3188.0 ± 692.7	2879.9 ± 813.6 *	2858.4 ± 785.5 *	2654.4 ± 939.3 *	2666.8 ± 886.0 *	2802.6 ± 806.4 *	2867.8 ± 771.8 *
Gestational age (wk), mean ± SD	38.1 ± 2.5	36.9 ± 3.3 *	36.8 ± 3.0 *	35.9 ± 4.0 *	36.2 ± 3.8 *	36.8 ± 3.1 *	37.0 ± 2.9 *
Infant sex, male, n (%)	1985 (51.5)	216 (56.0)	97 (61.8)	76 (54.3)	42 (50.0)	71 (57.7)	64 (59.3)
Childcare at 4m, n (%)	1280 (51.4)	126 (53.6)	50 (55.6)	46 (58.2)	31 (64.6)	46 (60.5)	23 (46.0)
Singleton, n (%)	3029 (78.5)	249 (64.5) *	97 (61.8) *	83 (59.3) *	51 (60.7) *	76 (61.8) *	64 (59.3) *
Delivery method, n (%)							
Spontaneous vaginal delivery	1908 (49.5)	154 (40.0) *	59 (37.6) *	54 (38.6) *	34 (41.0)	44 (35.8) *	38 (35.2) *
Cesarean	1823 (47.3)	227 (59.0) *	98 (62.4) *	85 (60.7) *	49 (59.0)	78 (63.4) *	68 (63.0) *
Other [b]	122 (3.2)	4 (1.0) *	0 (0) *	1 (0.7) *	0 (0)	1 (0.8) *	2 (1.9) *

Note: ASQ, Ages & Stages Questionnaire; HS, high school; GED, General Educational Development; BMI, body mass index. Continues characteristics were compared between fail vs. no fail in the domain using t tests, and categorical characteristics were compared between fail vs. no fail in the domain using chi-square tests. Children with all 5 domains missing at baseline were excluded (n = 491). Missing in specific domains: fine motor (n = 40), gross motor (n = 39), communication (n = 36), personal-social (n = 35), problem solving (n = 54). Any fail indicates the child failed any of the 5 domains of ASQ. No fail indicates the child did not fail any of 5 domains ASQ when missing in specific domains were treated as no fail. Missing in covariates: paternal age (n = 282), paternal education (n = 92), marital status (n = 55), insurance (n = 3), pre-pregnancy BMI (n = 6), paternal BMI (n = 343), any alcohol during pregnancy (n = 1), childcare at 4m (n = 1521), and delivery method (n = 6).

* *p*-values <0.05.

[a] Medicaid, State specific plan, Military health care, Indian health service, Medicare, other.

[b] Others include forceps delivery, vacuum extraction.

Table 2

Adjusted odds ratios of failing any domain or specific domain in the ASQ screening in association with indoor air pollution exposure throughout the study period (n = 4735).

Exposure	Any fail	Fine motor	Gross motor	Communication	Personal-social	Problem-solving
Cooking fuels	**1.28 (1.07, 1.53)**	1.34 (0.98, 1.84)	**1.52 (1.09, 2.13)**	1.25 (0.91, 1.70)	**1.36 (1.00, 1.85)**	1.15 (0.84, 1.60)
Heating fuels	0.89 (0.71, 1.13)	1.02 (0.70, 1.50)	0.97 (0.63, 1.49)	1.05 (0.71, 1.54)	1.02 (0.67, 1.54)	1.12 (0.76, 1.66)
Passive smoke	0.93 (0.68, 1.26)	1.16 (0.69, 1.94)	1.05 (0.59, 1.87)	0.72 (0.40, 1.28)	0.91 (0.54, 1.54)	1.15 (0.71, 1.87)

Note: ASQ, Ages & Stages Questionnaire. Generalized estimating equations adjusted for covariates provided adjusted odds ratios and 95% confidence intervals. Electricity used as the referent group for cooking fuel; Electricity/solar used as the referent group for heating fuel; No passive smoke exposure used as the referent group for passive smoking.

Models adjusted for maternal age, maternal race/ethnicity, maternal education, paternal education, insurance status, pre-pregnancy body mass index, marital status, plurality, active smoking, and passive smoking.