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Effects of a liquefied petroleum gas stove and fuel intervention and air pollution exposure on early childhood development: Findings from the household air pollution intervention network trial

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ABSTRACT

Background: Early Child Development (ECD) encompasses physical, cognitive, social, and emotional changes during childhood. Air pollution exposure has been associated with ECD delays. The Household Air Pollution Intervention Network (HAPIN) randomized controlled trial evaluated the health effects of a liquefied petroleum

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Household air pollution
Particulate matter
Exposure–response
Intention-to-treat

gas cookstove and fuel intervention during pregnancy and infancy. Here we present the intervention effect and exposure–response relationship between fine particulate matter ($PM_{2.5}$) and ECD.
Methods: The HAPIN trial enrolled 3195 pregnant women in rural Guatemala, Peru, India, and Rwanda. ECD was assessed at 12 months of infant age using the Caregiver Reported Early Development Instruments (CREDI). Personal 24-hr $PM_{2.5}$ exposure was measured from baseline through 12 months. Linear regression analyses were conducted to evaluate intervention effects on overall and domain-specific CREDI scores and exposure–response relationships between prenatal and postnatal $PM_{2.5}$ and infant development.
Results: Of 3061 live births, 2446 (79.9%) had valid CREDI assessments at 12 months. Despite substantial reductions in personal $PM_{2.5}$ exposures, the intervention did not have a significant effect on the overall age-standardized ECD score (adjusted mean difference 0.033, 95% CI: −0.023 to 0.088) or on sub-domain age-standardized scores. Subgroup analyses revealed that the intervention improved CREDI scores among infants whose mothers received the intervention before 18 weeks of gestation, and among female infants. No clear associations were observed between $PM_{2.5}$ exposure and CREDI scores at 12 months.
Discussion: While the LPG stove intervention did not affect ECD outcomes, variations in timing and sex-specific differences may play a role in shaping intervention effectiveness, similar to findings we previously reported for birth outcomes.

1. Introduction

Increasing inequities in early child development highlight the importance of identifying risk and protective factors that can be addressed through scalable interventions (Hertzman, 1998; Knudsen, 2004; National Research Council (US) and Institute of Medicine (US) Committee on Integrating the Science of Early Childhood Development, 2000; Shonkoff, 2003). Despite the higher burden of risk factors for developmental delays found in low- and middle-income countries (LMICs), most research on child development has been conducted in high-income countries (HICs). This disparity is particularly concerning since findings from HICs fail to represent the broader global population (Henrich et al., 2010). Therefore, factors identified through research in HICs need to be evaluated within LMICs to determine their applicability in different contexts.

Based on proxy measures such as stunting and poverty, it is estimated that 43% of children worldwide are at risk of not achieving their full developmental potential (Black et al., 2017; Grantham-McGregor et al., 2007) . Delays in developmental milestones in early childhood are associated with adverse social, economic, and health outcomes later in life (Moore, 2024). In HICs, where standardized childhood screening is more prevalent than in LMICs, estimates indicate that 6–30% of infants at or around 12 months of age exhibit developmental delays (Simpson et al., 2003; Slykerman et al., 2007; Valla et al., 2015). Even in HICs, the rates of screening for delays in Early Child Development (ECD) vary considerably at the sub-national level (Hirai et al., 2018). In LMICs, estimates are based on national demographic and health surveys that use rapid screening tools to assess ECD delays in children over 2 years of age (Gil et al., 2020). Analyses of the UNICEF caregiver-reported Early Childhood Development Index indicate that 81 million (33%) children ages 3 and 4 years in LMICs exhibited low cognitive and/or social-emotional development (Gil et al., 2020; McCoy et al., 2016).

A growing body of work has begun to elucidate the factors that may influence child development. Factors like socioeconomic status (e.g., income and education), women's empowerment, parental distress (e.g., stress, depression, anxiety, and other forms of psychopathology), child stimulation, and physical environmental exposures (e.g., household air pollution) have been identified as potential contributors that may affect early child development outcomes (Black and Kowalski, 2021; Jensen et al., 2017). Although many of these contributing factors have been extensively studied as potential independent influences on child development, there is limited research disentangling the interacting mechanisms and timing effects of these factors. Additionally, there is relatively limited research investigating ECD outcomes in very early childhood (e.g., 12 months or under), a period that may be a sensitive window of exposure (Nelson and Gabard-Durnam, 2020), as well as across diverse cultural contexts.

Among the potential determinants of early child development outcomes, exposure to air pollution may be particularly important in LMICs, where the widespread reliance on biomass fuels increases the risk of exposure. It is estimated that almost half of the world's population continues to rely on biomass fuels for cooking or heating in the home (Health Effects Institute, 2020). Exposure to fine particulate matter [particulate matter with an aerodynamic diameter $\leq 2.5\ \mu m$ ($PM_{2.5}$)], black carbon (BC), carbon monoxide (CO), and nitrogen dioxide (NO_2) from the combustion of biomass fuels during pregnancy has been associated with adverse health outcomes, including preterm birth and small for gestational age (SGA) in infants and growth faltering and developmental delays during childhood (Mertens at al., 2023; Younger et al., 2022). Many studies have found associations between prenatal exposure to air pollution and adverse neurodevelopment outcomes in childhood (Volk et al., 2020). For instance, prenatal exposure to particulate matter has been associated with lower scores across developmental domains in infants from 6 to 24 months, with the most salient effects at earlier time points and attenuating with age (Kim et al., 2014; Su et al., 2022).

Estimating the prevalence of delays in developmental milestones can pose methodological challenges, as there are numerous standardized instruments for assessing child development, each with unique strengths and varying levels of adaptation to different cultural settings (Grantham-McGregor et al., 2007). ECD can be rapidly evaluated using screening tools such as the Ages and Stages Questionnaire (Squires and Bricker, 2012); however, while these tools are effective for identifying broader developmental delays, they may not be sensitive enough to detect more subtle developmental delays in infants (Fernald et al., 2009). More formal assessment tools, such as the Bayley Scales of Infant and Toddler Development (BSID), are considered the gold standard method for evaluating ECD in clinical and research settings (Bayley and Aylward, 2019). However, their implementation can be expensive and requires professionally trained assessors, making them less feasible for use in large-scale studies (Anderson and Burnett, 2017; Brito et al., 2019). Another challenge is that screening tools and assessments are often developed and validated in high-income Western countries, potentially limiting their interpretability in low-income and international settings. In response to this need, the Caregiver Reported Early Development Instruments (CREDI) was designed to evaluate ECD among children residing in LMICs, and has been extensively validated and standardized for use in these settings(Altafim et al., 2020; Li et al., 2020; McCoy et al., 2017, 2018, 2021)

Numerous studies have assessed the effect of interventions aimed at reducing exposure to air pollution from biomass fuel use on maternal and child health. Yet, an interventional effect on early child development during the first year of life has not been evaluated at scale (Alderman et al., 2021). The multi-country Household Air Pollution Intervention Network (HAPIN) trial was conducted to evaluate the effect of a liquefied petroleum gas (LPG) cookstove and fuel intervention on four primary outcomes: birthweight, infant stunting, severe pneumonia in infants, and blood pressure in adult women aged 40 to 79 years. A secondary outcome of the trial was ECD at 12 months of age (Clasen et al., 2020). Here, we report on the effect of the LPG stove and fuel intervention on early child development at 12 months and evaluate the exposure–response associations between $PM_{2.5}$ and early child development at 12 months.

2. Methods

2.1. Study design and participants

The design and overall methods of the HAPIN trial have been reported elsewhere (Clasen et al., 2020). The trial enrolled 3200 pregnant women, 800 each in Guatemala, India, Peru, and Rwanda, and randomly assigned half to the intervention group and half to the control group. In India and Peru, to ensure balance between different geographic regions participating in the study, additional stratified randomization was used (India = 2 regions; Peru = 6 regions). Women were screened at prenatal clinics and were eligible to enroll in the trial if they were 18 to < 35 years old, had a viable singleton pregnancy between 9 to 19 weeks of gestation verified by abdominal ultrasound, and lived in a household that predominantly used a biomass stove. Women who reported smoking were excluded from the trial.

Participants in the intervention group were provided with a free LPG stove and unlimited fuel for almost 18 months, during their pregnancy and the first year of infant life. They were encouraged to use the LPG stove exclusively for cooking, avoiding the use of the biomass stove. Intervention adherence (use of stoves measured by temperature sensors) and fidelity (stove and fuel delivery) demonstrated near exclusive use of LPG (Quinn et al., 2021). Women assigned to the control group continued using biomass stoves as their primary cooking method. After birth, infants were followed during their first year of life. For this study, we included infants with a valid CREDI assessment at the 12-month visit.

2.2. Measurement of personal exposure to air pollutants

We assessed personal exposure to air pollutants using wearable instruments, described in detail elsewhere (Johnson et al., 2020). We used the RTI Enhanced Children's MicroPEM (ECM, RTI International) to measure personal exposure to $PM_{2.5}$. We conducted 24-hour exposure assessments six times: baseline before randomization (9–25.4 weeks of gestation), two time points after randomization (19–34.3 and 24.9–40.4 weeks of gestation), and three times during the postnatal period (around infant ages 3, 6, and 12 months). During each exposure assessment, we asked the participants to wear the instruments to perform direct assessments, and post-birth we deployed instruments at stationary home locations (microenvironments) to measure pollutant concentrations in different microenvironments. Due to the difficulty of fitting an infant with a monitor, we reconstructed infants' exposures indirectly using Bluetooth receivers collocated with air sampling instruments worn by their mothers and placed in microenvironments, along with small Bluetooth emitter beacons worn by the infants. Briefly, gravimetrically-corrected, real-time nephelometric $PM_{2.5}$ concentrations from the closest microenvironment were integrated for each period the infants spent in its vicinity, as determined by the strength of the signal from the infants' emitter (Liao et al., 2020; Pillarisetti et al., 2023a). The exposure contrasts between the intervention and control arms of the trial have been reported in detail elsewhere for the pregnant women during the gestational period (Johnson et al., 2022) and for the first year of infant life (Pillarisetti et al., 2023a).

2.3. Early child development assessment and outcomes

We used the Caregiver Reported Early Development Instruments (CREDI) to evaluate infants at 12 months of age. The CREDI Long Form is an open-source instrument that can be used from birth to three years of age. It consists of up to 108 items evaluating the infant's ability to use fine and gross motion (motor domain); communicate their needs and desires (language domain); demonstrate attention, memory, perception, problem-solving abilities, and basic knowledge acquisition (cognitive domain); and regulate behaviors and emotions, understand feelings, and ability to interact well with others (social-emotional domain) (McCoy et al., 2017). The instrument also provides an overall score, summarizing aspects of all four specific domains.

The CREDI instrument has been tested in over 17 LMICs and HICs and was designed to be linguistically and culturally neutral (McCoy et al., 2018). The CREDI has demonstrated good construct validity, capturing differences between the four evaluated domains (Waldman et al., 2021). It has demonstrated good discriminant validity (e.g., variation in scores depending on anthropometrics and caregiver education level), internal consistency and test–retest reliability. Finally, the scores for each domain correlate with results from the BSID (Alderman et al., 2021; Altafim et al., 2020; McCoy et al., 2021, 2018, 2017; Waldman et al., 2021).

The CREDI was translated to Spanish by McCoy and colleagues. This version was used in our two Spanish-speaking countries (Guatemala and Peru). We followed the CREDI protocol for translating the CREDI long form into Kinyarwanda and Tamil languages, then back-translated into English and forward-translated again to compare items and to ensure consistency and alignment with the original instrument. Other than translating it into local languages, we did not make any adaptations to the instrument. All supervisors and field workers were trained through an online webinar that provided an overview of the CREDI, using the assessor manual to provide full item descriptions to the field workers. Additional in-person training was provided for each site over a 1-week period. Finally, each field worker administered the CREDI to 5 pilot caregivers before administering the questionnaire to official study participants. These administrations were supervised. Because the CREDI has been well validated in over 17 countries we did not validate the CREDI in the HAPIN trial.

The CREDI Long Form took about 20–30 min to complete. The assessment was initiated at specific items based on the infant's exact age (e.g., item 6 for infants younger than 12 months of age, item 12 for infants 12 months of age or older). The primary caregiver was asked whether they had observed behaviors related to the four developmental domains. Assessors stopped after receiving five consecutive negative answers. Caregiver responses were recorded on tablets using digital questionnaires. We used REDCap forms hosted at Emory University (Jabbarzadeh et al., 2024).

During the trial, quality assurance efforts were implemented by the data management team every 1–3 months to ensure that the correct stopping and starting points were used in the long-form, to provide feedback to assessors in order to minimize missing data, and to ensure that reverse-coding was being used appropriately. In preparation for this analysis, extensive data cleaning was performed by two independent researchers on the CREDI data collected in HAPIN (see Supplemental Material, Appendix A for data cleaning, processing, and quality control). Data were processed following the instructions from the CREDI development team. Responses were scored using the R package *credi* developed by the CREDI team. The outcomes for this analysis were the norm-referenced age-standardized z-score for overall and domain-specific CREDI scores (Seiden et al., 2023).

2.4. Covariates

We assessed the balance between intervention and control groups in terms of participant and household characteristics linked to early child development. We assessed socioeconomic status (SES) at baseline for each household via principal component analysis (PCA) with an inventory of household characteristics, access to infrastructural services, a list of appliances based on the Equity Tool (Metrics for Management, 2024), and crowding. We calculated a SES score based on the first component of the PCA (see **Supplementary Material**, Appendix B for procedure for socioeconomic status score).

Maternal dietary diversity at baseline was assessed with questions adapted from the Food and Agriculture Organization of the United Nations Minimum Diet Diversity for Women, with a score ranging from 0 to 10 based on the consumption of ten specific food groups within the previous 30 days, indicating adequate micronutrient intake (< 4, low; 4–6, medium; 5–10, high; missing) (FAO and FHI 360, 2016). The Food and Agriculture Organization Food Insecurity Experience Scale was used to assess food insecurity in the household during the 30 days prior to baseline, including questions about uncertainty about food access, insufficient quality of available food, and insufficient food intake, with the number of affirmative answers representing the extent of food insecurity (0, food secure; 1 to 3, mild; 4 to 8, moderate/severe; missing) (Swindale and Bilinsky, 2006).

2.5. Statistical analysis

Our statistical analysis followed pre-specified plans before the release of the unblinded data from the HAPIN Data Management Core (see **Supplementary Material**, Appendix C for statistical analysis plan). The sample size and power for the trial were based on the intention-to-treat analyses for the primary outcomes. There were no sample size calculations for the secondary outcomes. We present the results of statistical analyses using 95% confidence intervals. We used linear regression to evaluate the effect of the intervention on overall and cognitive, motor, language, or social-emotional domain age-standardized ECD scores at 12 months under intention-to-treat, with the trial group assignment (stove intervention, control group as the reference) as the main covariate, adjusted by randomization strata (2 sites in India, 6 sites in Peru, 1 site in Guatemala, and 1 site in Rwanda). We assessed effect modification by country, infant sex, gestational age at intervention, and SES level at baseline using subgroup analyses.

We estimated the average personal exposure to $PM_{2.5}$ for pregnant mothers during gestation (at most three measurements) and for infants during the postnatal period (at most three measurements). For participants in the control group, the average exposure during the gestational period was estimated using all available gestational maternal measures (max n = 3). For the women in the intervention group, the gestational average maternal exposures were weighted for the time before and after the intervention was delivered (Johnson et al., 2022). Gestational days before LPG installation were assigned the single maternal measurement obtained at baseline, and the gestational days following intervention with LPG were assigned the average of up to two post-randomization gestational maternal measurements. Exposure-response analyses were performed to estimate the association between exposure to $PM_{2.5}$ and the overall, cognitive, motor, language, and social-emotional domain CREDI scores.

We used linear models to estimate the joint association between gestational and postnatal $PM_{2.5}$ exposures, and the overall and domain-specific CREDI scores at 12 months of age. We assessed non-linearity in the exposure–response using log-transformed exposures, quartile regression, and models using cubic splines for the exposure. We performed sensitivity analyses including observations with missing values in the postnatal infant exposure, using maternal postnatal exposure as a proxy to impute missing values.

The exposure–response models were adjusted for country (Peru, Guatemala, Rwanda, India), infant sex (male, female), maternal education (no education, primary incomplete, primary complete, secondary incomplete, secondary complete, vocational and some college), and SES. Effect modification for the exposure–response analysis was assessed with sub-group analyses for study country, maternal age at baseline, nulliparity, gestational age at baseline (<18 weeks, >= 18 weeks), dietary diversity at baseline, household food insecurity score at baseline, and preterm birth (<37 weeks gestation). All analyses were performed using R version 4.5.1 (2025–09-01) (R Core Team, 2022).

2.6. Ethics review and trial registration statement

The study protocol was reviewed and approved by institutional review boards (IRBs) or Ethics Committees at Emory University (00089799), Johns Hopkins University (00007403), Sri Ramachandra Institute of Higher Education and Research (IEC-NI/16/JUL/54/49) and the Indian Council of Medical Research – Health Ministry Screening Committee (5/8/4–30/(Env)/Indo-US/2016-NCD-I), Universidad del Valle de Guatemala (146–08-2016) and Guatemalan Ministry of Health National Ethics Committee (11–2016), Asociación Benéfica PRISMA-Peru (CE2981.17; CE2008.18; CE0028.20; CE0291.21), the London School of Hygiene and Tropical Medicine (11664) and the Rwandan National Ethics Committee (853/RNEC/2016; 317/2017; 357/2018; 194/2019; 929/2020; 64/2021), and Washington University in St. Louis (201611159). Pregnant women provided written informed consent in local languages, obtained by trained fieldworkers. If women had low literacy, the consent was read to them in the presence of a witness and a thumbprint indicating consent was obtained. The study has been registered with ClinicalTrials.gov (Identifier NCT02944682).

3. Results

3.1. Participant characteristics

Between April 2018 to February 2020, 3200 women were enrolled across four countries. Five withdrew from the trial after randomization upon determining they were ineligible, resulting in 1590 women randomized to the intervention arm and 1605 to the control arm. A total of 67 participants had a pregnancy loss, and 67 participants left the study for other reasons before giving birth. A total of 3061 infants were born to HAPIN participants, 64 of whom died before 12 months of age, and 48 left the study before the 12-month assessment for other reasons. Of 3061 live births, 2949 (96.3%) infants were still enrolled in the trial at 12 months, 2502 (81.7%) infants were assessed for ECD using the CREDI, and 2446 (79.9%) had a valid CREDI assessment (Fig. 1). Of the 559 CREDI assessments missed at 12 months, 457 (81%) were scheduled during the beginning of the COVID-19 pandemic (March 2020 to October 2020), with resumption of household visits varying by country and based on local permissions (See Supplementary Appendices, **Table A4**; Supplementary Tables and Figures, **Fig. S1**). Eight CREDI assessments were missed in India during that period because phone interviews were used in that country to perform ECD assessments during the lockdowns. Of the 56 CREDI assessments that were not deemed valid, 11 missed items that should have been included at the beginning of the interview given the age of the infant, and 45 stopped the interview before finding the stopping pattern (Supplementary Appendices, **Table A9**).

Over half of the mothers across all countries were younger than 25 years (range 18 to 35), shorter than 152 cm (range 101.3 to 178.3, 11 missing), and had a BMI above 23 kg/m^2 (range 13.3 to 44.2, 18 missing) (Table 1). Overall, maternal educational completion within all countries was distributed evenly between the different achievement levels (no formal education or primary school incomplete, primary school complete or secondary school incomplete, and secondary school complete or vocational or some college or university), but mothers in Peru tended to have more education above secondary school and more mothers in Guatemala and Rwanda tended to have incomplete primary or no formal education. Maternal dietary diversity at baseline tended to be low (56.3%) or medium (32.1%) across the study, except for, Peru where 90% had medium or high dietary diversity scores (Supplementary Tables and Figures, **Table S1**).

There were a few differences between those who had a valid CREDI assessment at 12 months and those who had a missing assessment or CREDI scores that were deemed invalid (Table 1). Among the group excluded from the analysis, women had higher completion rates of secondary school (28.6%, vs 23.3% in the included group), lower

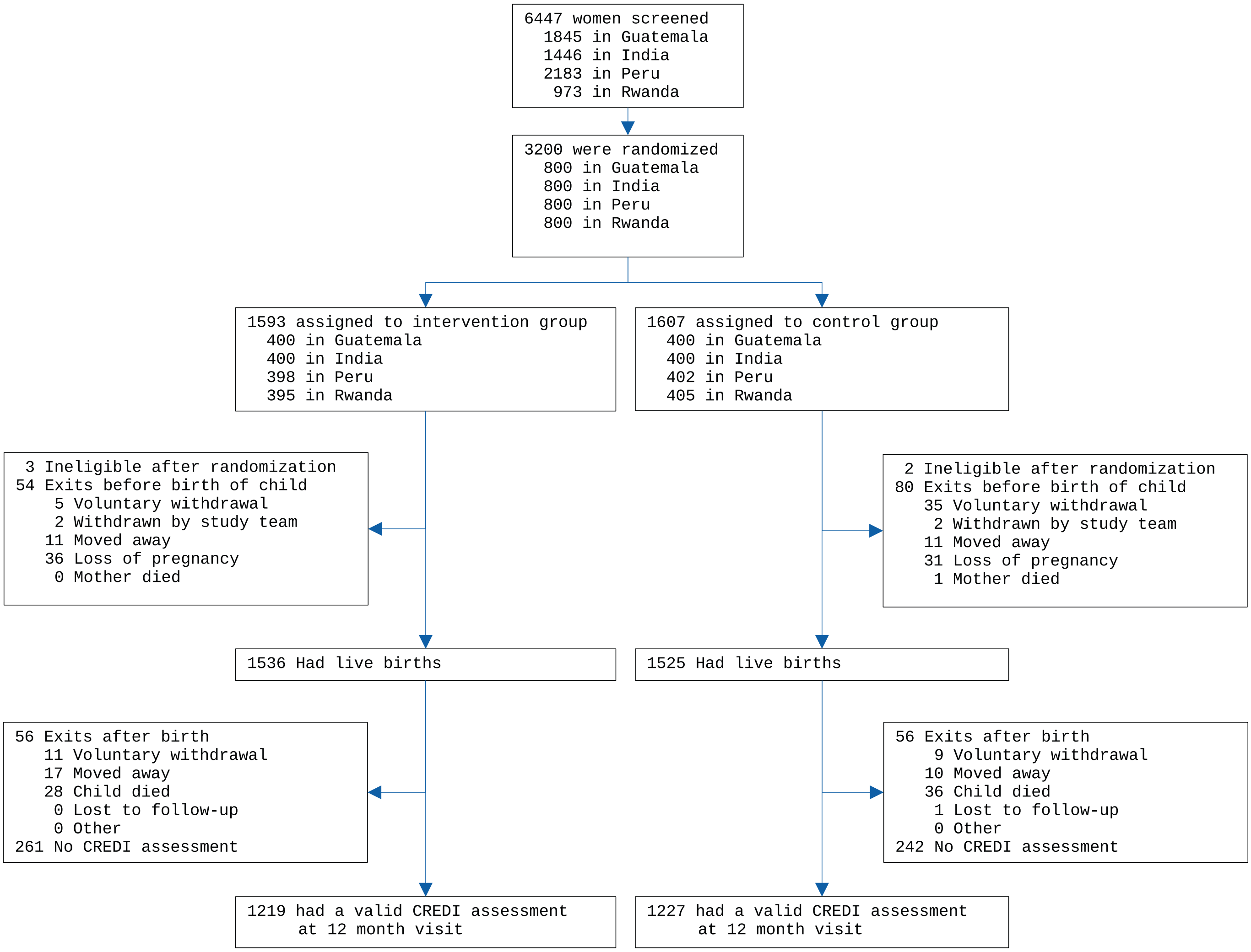

Fig. 1. Screening, randomization, and follow-up. The boxes show the number of pregnant women or infants included at each stage in the study through 12-month CREDI assessment.

exposures to secondhand smoke (4.6%, vs 11.9% in the included group), and higher levels of moderate or severe household food insecurity (20.0%, vs 13.9% in the included group). They were less likely to be nulliparous (33.5%, vs 39.3% in the included group) and more likely to deliver a pre-term infant (8.1%, vs 5.0% in the included group). The characteristics of infants were generally similar between intervention and control groups in the group that had a valid CREDI assessment at 12 months. Of note, mothers in the intervention group had higher dietary diversity (12.8%) at baseline than those in the control group (9.2%).

3.2. *Intervention fidelity and adherence; effects on $PM_{2.5}$*

Throughout the study, households in the intervention arm received free fuel refills for their LPG cookstoves and study personnel visited them regularly to assess if they were using biomass stoves, providing behavioral reinforcement to encourage LPG stove use and offering stove maintenance. The trial achieved high adherence and fidelity, with over 96% of participants in the intervention arm cooking exclusively using LPG and fewer than 4% reporting ever running out of fuel (Quinn et al., 2021). The intervention resulted in lower gestational and postnatal 24-hour personal exposures to fine particulate matter than the control (mean prenatal exposure, 35.0 $\mu g/m^3$ vs. 103.3 $\mu g/m^3$; mean postnatal exposure, 37.9 $\mu g/m^3$ vs. 109.2 $\mu g/m^3$, representing a 70% contrast between intervention and control arms (Johnson et al., 2020; Pillarisetti et al., 2023a). Table 2 summarizes the overall exposure values for each period for the participants in the present study.

3.3. *Early child development assessment and outcomes*

Infants in this study tended to have lower ECD scores than the global CREDI norm-referenced population (Table 3). Notably, infants from India tended to have higher overall and motor scores, and slightly higher cognitive and social-emotional scores for their age than infants from the other countries in our study. Infants from Guatemala and Peru had lower norm-referenced standardized scores than infants from Rwanda and India, across all domains.

3.4. *Effect of the HAPIN LPG intervention on ECD*

The intention-to-treat analysis included all 2446 infants with a valid CREDI assessment at the 12-month visit (1219 intervention, 1227 control). The LPG stove and fuel intervention had no effect on early child development at 12 months for the overall CREDI score (adjusted mean difference *0.033;* 95% CI: −0.023 to 0.088) or on domain-specific scores (Table 4).

Subgroup analyses suggest that the intervention had a protective effect on early child development at 12 months among infants born to trial participants who received the LPG stove before 18 weeks of gestation. This was observed for the age-standardized overall (adjusted mean difference *0.1;* 95% CI: 0.032 to 0.169) and domain-specific

Table 1
Characteristics of participants from households with a live birth.

Characteristics	Infants included in analysis Intervention (n = 1219)	Control (n = 1227)	Infants excluded from analysis Intervention (n = 317)	Control (n = 298)
Maternal factors				
Mother's age [years, median (IQR)]	24.7 (6.8)	25 (7.3)	25.2 (7.7)	25.1 (7.6)
Mother's height [cm, median (IQR)]	152 (8.2)	152.1 (7.7)	152.3 (7.4)	151.7 (8.1)
Mother's body mass index [kg/m2, median (IQR)]	22.7 (5.4)	22.5 (5.2)	23.7 (5)	23.5 (4.4)
Mother's highest level of education completed, n (%)				
No education	83 (6.8)	127 (10.4)	13 (4.1)	15 (5)
Primary incomplete	288 (23.6)	321 (26.2)	77 (24.3)	77 (25.8)
Primary complete	235 (19.3)	217 (17.7)	60 (18.9)	60 (20.1)
Secondary incomplete	191 (15.7)	190 (15.5)	52 (16.4)	47 (15.8)
Secondary complete	299 (24.5)	273 (22.2)	96 (30.3)	80 (26.8)
Vocational	37 (3)	32 (2.6)	12 (3.8)	15 (5)
Some college	86 (7.1)	67 (5.5)	7 (2.2)	4 (1.3)
Mother's minimum dietary diversity at baseline, n (%)[a]				
Low	691 (56.7)	717 (58.4)	162 (51.1)	154 (51.7)
Medium	372 (30.5)	397 (32.4)	111 (35)	104 (34.9)
High	156 (12.8)	113 (9.2)	44 (13.9)	39 (13.1)
Missing				1 (0.3)
Pregnancy factors				
Nulliparous, n (%)				
No	711 (58.3)	770 (62.8)	204 (64.4)	203 (68.1)
Yes	505 (41.4)	456 (37.2)	112 (35.3)	94 (31.5)
Missing	3 (0.2)	1 (0.1)	1 (0.3)	1 (0.3)
Gestational age at baseline [weeks, median (IQR)]	15.4 (5)	15.1 (5.1)	15.7 (5.1)	15.1 (4.6)
Household factors				
Household food insecurity score (baseline), n (%)[c]				
None	743 (61)	705 (57.5)	161 (50.8)	115 (38.6)
Mild	309 (25.3)	312 (25.4)	94 (29.7)	112 (37.6)
Moderate/severe	148 (12.1)	192 (15.6)	60 (18.9)	67 (22.5)
Missing	19 (1.6)	18 (1.5)	2 (0.6)	4 (1.3)
Number of improved structures, max = 4 (baseline) [median (IQR)][d]	2 (1)	2 (1)	3 (1)	2 (1)
Number of appliances, max = 20 (baseline) [median (IQR)][e]	4 (3)	4 (3)	4 (3)	4 (3)
Number of infrastructural services, max = 6 (baseline) [median (IQR)][f]	3 (2)	3 (2)	3 (2)	3 (1)
Number of people who sleep in the house [median (IQR)]	4 (2)	4 (2)	4 (2)	4 (3)

Table 1 (*continued*)

Characteristics	Infants included in analysis Intervention (n = 1219)	Control (n = 1227)	Infants excluded from analysis Intervention (n = 317)	Control (n = 298)
Socioeconomic score (baseline) [median (IQR)][g]	0.02 (1.69)	−0.09 (1.78)	−0.41 (0.93)	−0.44 (1.06)
Secondhand smoking, n (%)				
No	1083 (88.8)	1070 (87.2)	306 (96.5)	279 (93.6)
Yes	136 (11.2)	156 (12.7)	10 (3.2)	18 (6)
Missing		1 (0.1)	1 (0.3)	1 (0.3)
Child factors				
Child stimulation, n (%)				
Low	297 (24.4)	299 (24.4)	26 (8.2)	24 (8.1)
Moderate	569 (46.7)	593 (48.3)	37 (11.7)	31 (10.4)
High	353 (29)	335 (27.3)	57 (18)	60 (20.1)
Missing			197 (62.1)	183 (61.4)
Preterm, n (%)[b]				
No	1156 (94.8)	1167 (95.1)	290 (91.5)	275 (92.3)
Yes	63 (5.2)	60 (4.9)	27 (8.5)	23 (7.7)
Infant sex, n (%)				
Female	588 (48.2)	603 (49.1)	148 (46.7)	135 (45.3)
Male	631 (51.8)	624 (50.9)	169 (53.3)	163 (54.7)
Age at CREDI assessment [months, median (IQR)]	12 (0.4)	12 (0.4)		
Gestational age at birth [weeks, median (IQR)]	39.6 (1.7)	39.4 (1.6)	39.4 (2)	39.4 (1.6)
Country, n (%)				
Guatemala	288 (23.6)	287 (23.4)	96 (30.3)	99 (33.2)
India	378 (31)	375 (30.6)	10 (3.2)	12 (4)
Peru	275 (22.6)	252 (20.5)	110 (34.7)	106 (35.6)
Rwanda	278 (22.8)	313 (25.5)	101 (31.9)	81 (27.2)

[a] Adapted from Food and Agriculture Organization of the United Nations Minimum Diet Diversity for Women.
[b] Gestational Age at Birth < 37 weeks.
[c] The Food and Agriculture Organization Food Insecurity Experience Scale was used to assess food insecurity during the previous 30 days.
[d] Number of structures build using improved materials. Includes roof, walls, and floor.
[e] Number of appliances and other assets (listed in the supplemental information).
[f] Access to infrastructural services (electricity, cable TV, internet, improved toilets, improved water sources, bank account).
[g] Composite score based on household characteristics, appliances and other assets, and access to services. Calculated using the first component of a principal component analysis. A higher score represents a higher socioeconomic status.

CREDI scores (adjusted mean differences: cognitive *0.086;* 95% CI: 0.012 to 0.16; motor, *0.068;* 95% CI: 0.004 to 0.131; language, *0.147;* 95% CI: 0.065 to 0.228; and social-emotional, *0.09;* 95% CI: 0.008 to 0.173) (Fig. 2). We also observed a protective effect of the intervention for female infants, on the overall, motor, and language domains age-standardized CREDI scores (adjusted mean differences: overall, *0.091*; 95% CI: 0.012 to 0.17; motor, *0.075*; 95% CI: 0.002 to 0.149; and language, *0.12*; 95% CI: 0.025 to 0.214). Considerable variation was

Table 2
Summary of period-average personal exposures to $PM_{2.5}$ by country, all participants.

Country	Period, median (IQR), n		
	Gestational (ug/m3), n	Postnatal (ug/m3), n	Postnatal, with proxy (ug/m3), n[a]
Overall	**69.7 (74.9), 2770**	**35.2 (51.5), 2020**	**37.4 (51), 2879**
India	69.3 (66.8), 712	42.4 (61.7), 626	45.3 (70.1), 756
Rwanda	75.6 (66.8), 717	42.2 (32.8), 345	45.1 (31.8), 719
Guatemala	89.1 (92.6), 721	41.6 (82), 658	42.2 (78.2), 751
Peru	38.9 (57), 620	16.4 (7.9), 391	16.3 (14), 653

[a] Maternal exposure measures used as a proxy when infant measures were missing.

observed for the effect of the intervention between participants from the four study countries, with participants from India having a higher age-standardized language score in the intervention group (adjusted mean difference *0.139;* 95% CI: 0.019 to 0.258). The effect did not vary considerably for participants given SES at baseline.

3.5. Associations between exposure to air pollution and early child development

Linear models with untransformed or log-transformed exposures did not show consistent associations between gestational or postnatal exposures to $PM_{2.5}$ and the overall or domain-specific CREDI scores (Table 5; Supplementary Tables and Figures, Tables S4 and S5). Compared to the lowest quartile, infants in the higher $PM_{2.5}$ quartile showed very small and inconsistent differences in overall ECD score; however, none of these reached statistical significance or were clinically meaningful (Table 6). Likewise, cubic spline models did not show a trend in age-standardized overall CREDI score at higher exposures compared to the first quartile for both the gestational and postnatal periods (Fig. 3).

Sensitivity analyses using the maternal postnatal exposures to $PM_{2.5}$ as a proxy for the missing infant exposures showed similar results with no significant associations observed between gestation and postnatal exposure and ECD scores in linear and log-linear analyses. Similar to the main analyses, the sensitivity analyses yielded consistent results for the quartile analyses.

We performed prespecified subgroup analyses by several maternal, pregnancy, child, and household factors. We observed a non-significant association between gestational and postnatal exposure to PM2.5 and CREDI scores across all subgroups (Fig. 4).

4. Discussion

The LPG stove and fuel intervention of the HAPIN randomized controlled trial did not improve early child development scores at 12 months. The lack of a significant overall effect of the LPG stove and fuel intervention on ECD scores at 12 months was not consistent with existing evidence from multiple observational studies that have demonstrated positive associations between air pollution exposures and adverse developmental outcomes, including cognitive delays and impaired motor skills (Gonzalez-Casanova et al., 2018; Kim et al., 2014; Lertxundi et al., 2015; Su et al., 2022; Volk et al., 2020). Consistent with our findings, a study in Peru nested within the HAPIN trial assessed ECD using the BSID in a subset of 301 children aged 24–36 months also found no effect on ECD in either intention-to-treat or exposure–response analyses of prenatal and postnatal PM 2.5 exposures (Reuland et al., 2025).

We observed effect modification that may provide evidence that timing and sex-specific differences can significantly influence the efficacy of the intervention. The LPG stove was delivered to pregnant women at a median gestational age of 17.9 weeks (interquartile range, 15.4 to 20.6 weeks) (Quinn et al., 2021). We found a protective effect among women who received the stove before 18 weeks, a finding that is consistent with the 33 g borderline significant greater birth weight in these infants (Clasen et al., 2022) This indicates that reduced exposure to $PM_{2.5}$ during the first trimester may have a positive effect on overall and domain-specific child development outcomes. Notably, this is in contrast to observational studies that have shown that increased $PM_{2.5}$ in the second and third trimester has a larger effect than earlier trimesters (Chiu et al., 2016; Hurtado-Díaz et al., 2021).

The HAPIN intervention achieved a substantial reduction in exposure in the intervention group during mid-to-late pregnancy, with median postnatal $PM_{2.5}$ measurements of 35.2 ug/m^3 (IQR, 51.5; n = 2020), yet we did not find a difference in CREDI scores. This

Table 4
Main outcomes of the ITT analysis of the HAPIN trial LPG intervention on age-standardized developmental milestones scores.

ECD domain	CREDI z-scores, mean ± sd[a]		Intervention effect (95% CI)[b]
	Intervention (n = 1219)	Control (n = 1227)	
Overall	−0.589 ± 0.796	−0.614 ± 0.789	0.033 (−0.023, 0.088)
Cognitive	−0.707 ± 0.773	−0.718 ± 0.781	0.017 (−0.043, 0.077)
Motor	−0.577 ± 0.791	−0.595 ± 0.784	0.025 (−0.026, 0.077)
Language	−0.75 ± 0.846	−0.802 ± 0.86	0.061 (−0.005, 0.127)
Socio-emotional	−0.59 ± 0.866	−0.596 ± 0.859	0.014 (−0.052, 0.081)

[a] Summary of the age-standardized overall and domain-specific scores.
[b] Mean differences for the score in each domain between the between intervention and control groups, adjusted for randomization strata (2 in India, 6 in Peru, 1 in Guatemala, and 1 in Rwanda).

Table 3
Summary of ECD scores at 12 months of age for each domain.

Country	Age-standardized scores, mean (sd)[a]					Raw CREDI scores by domain, mean (sd)[b]				
	Overall	Cognitive	Motor	Language	Socio-emotional	Overall	Cognitive	Motor	Language	Socio-emotional
Overall	−0.6 (0.79)	−0.71 (0.78)	−0.59 (0.79)	−0.78 (0.85)	−0.59 (0.86)	47.21 (0.96)	48.78 (0.56)	48.23 (0.73)	48.58 (0.6)	48.55 (0.58)
Guatemala	−0.95 (0.83)	−0.82 (0.87)	−1.11 (0.73)	−0.78 (1.02)	−0.68 (0.9)	46.83 (1.02)	48.74 (0.63)	47.76 (0.68)	48.6 (0.74)	48.52 (0.6)
India	−0.15 (0.69)	−0.52 (0.73)	−0.04 (0.67)	−0.69 (0.85)	−0.41 (0.9)	47.74 (0.86)	48.9 (0.52)	48.72 (0.64)	48.62 (0.6)	48.65 (0.61)
Peru	−0.99 (0.69)	−0.98 (0.8)	−0.93 (0.63)	−1.09 (0.78)	−0.89 (0.87)	46.74 (0.86)	48.6 (0.61)	47.92 (0.6)	48.36 (0.58)	48.36 (0.62)
Rwanda	−0.5 (0.6)	−0.62 (0.63)	−0.47 (0.59)	−0.6 (0.64)	−0.47 (0.67)	47.34 (0.69)	48.85 (0.43)	48.34 (0.55)	48.7 (0.42)	48.64 (0.43)

[a] Scores standardized for age against the global CREDI norm referenced population using the R package provided by the CREDI development team.
[b] ECD scores obtained using the Caregiver Reported Early Development Instruments.

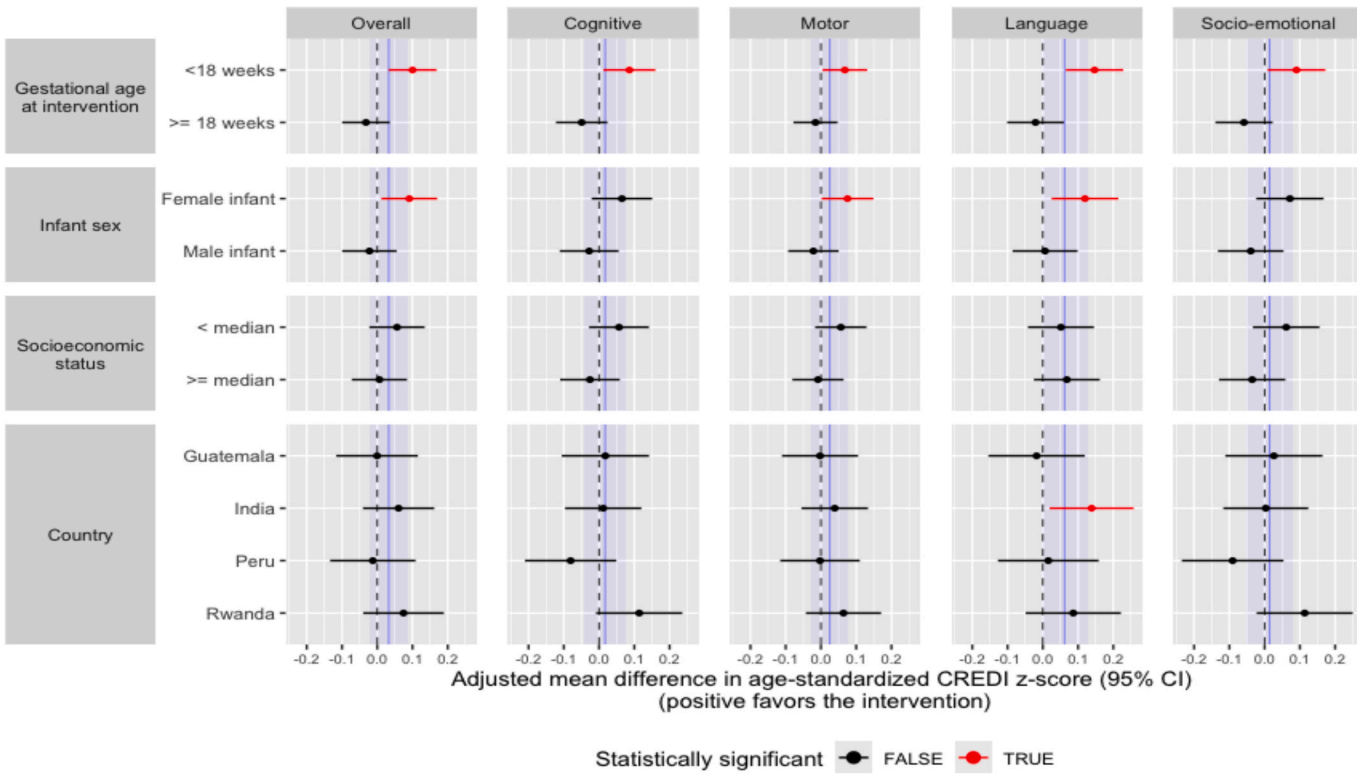

Fig. 2. Subgroup analyses for the effect of the intervention on the age-standardized overall and domain-specific CREDI scores at 12 months. This figure shows the effect of the intervention across all participants, and within the specified subgroups (rows), for each CREDI score (columns). The shaded area and solid vertical line represent the association for the overall study population, as a reference. Dashed line at 0 as a reference. Socioeconomic status (SES) calculated as a composite score based on an inventory of house characteristics, appliances, and access to infrastructural services (SES median = -0.14).

Table 5
Association between fine particulate matter exposure and age-standardized CREDI scores.

ECD domain[a]	Exposure	n	Estimate, change (95% CI)[b], [c] Gestational	Postnatal	R-squared	Akaike's Information Criterion[d]
PM 2.5						
Overall	linear	1482	−0.007 (−0.04, 0.026)	0.007 (−0.012, 0.026)	0.22	3212.3
	log-linear	1482	0.001 (−0.004, 0.006)	0 (−0.004, 0.004)	0.22	3212.7
Cognitive	linear	1482	−0.025 (−0.061, 0.011)	0.002 (−0.019, 0.022)	0.05	3431
	log-linear	1482	−0.003 (−0.008, 0.003)	−0.002 (−0.006, 0.003)	0.05	3431.1
Motor	linear	1482	0.002 (−0.029, 0.033)	0.006 (−0.012, 0.024)	0.33	2982.1
	log-linear	1482	0.003 (−0.002, 0.008)	0 (−0.004, 0.004)	0.33	2981.1
Language	linear	1482	−0.057 (−0.097, −0.017)	0.01 (−0.014, 0.033)	0.04	3781.1
	log-linear	1482	−0.007 (−0.013, −0.001)	0 (−0.005, 0.005)	0.04	3783.2
Socio-emotional	linear	1482	−0.02 (−0.06, 0.02)	−0.002 (−0.025, 0.022)	0.05	3808.2
	log-linear	1482	−0.002 (−0.008, 0.005)	−0.003 (−0.008, 0.002)	0.05	3807

[a] ECD z-scores obtained using the Caregiver Reported Early Development Instruments.
[b] Fully adjusted model, with covariates: country, infant sex, maternal education, and socioeconomic status.
[c] For linear exposure, the change in age-standardized score for an IQR change in the exposure; for log-linear exposures, the percent change in age-standardized score for a 10% increase in the exposure.
[d] Akaike's Information Criterion (AIC) is a statistical measure used to compare models, balancing goodness of fit and model complexity, with lower AIC values indicating models that fit better the data.

concentration is lower than the WHO Interim Target 3 (IT-3) mean concentration of 37.5 ug/m^3 (World Health Organization, 2021). However, other sources besides the stove likely contribute to this measured exposure, including household waste burning, outdoor fires used for heating water and preparing animal food, neighborhood cooking fires, crop residue burning, and road traffic (Pillarisetti et al., 2023a). That said, the beneficial impact on infants whose mothers received the intervention before 18 weeks of gestation underscores the importance of early intervention during critical periods of fetal development. This finding aligns with evidence that air pollution exposure during early gestation adversely affects fetal and infant development through several biological pathways, including increased inflammation, immune system disruption, and altered DNA methylation patterns (Singh et al., 2024). Evidence suggests that air pollution exposure during the preconception and periconception periods may have effects on subsequent child development.- (Blanc et al., 2023; Chen et al., 2024; Vohr et al., 2017). The observed sex-specific effects that we found align with existing literature demonstrating that male infants exhibit greater vulnerability to adverse developmental effects from environmental exposures (Moore, 2024), potentially due to an increased response to oxidative stress (Minghetti et al., 2013). These findings are consistent with ambient air pollution studies that found sex-specific differences in

Table 6
Change in the age-standardized CREDI scores by quartile of fine particulate matter exposure.

ECD domain[a]	n	Parameter[b]	Estimate, change (95% CI)[c] Gestational exposure	Postnatal exposure	R-squared	Akaike's Information Criterion[d]
PM 2.5						
Overall	1482	quartile 2	−0.067 (−0.173, 0.038)	−0.05 (−0.164, 0.065)	0.22	3214.6
		quartile 3	0.002 (−0.107, 0.111)	0.034 (−0.081, 0.15)	0.22	
		quartile 4	0.008 (−0.103, 0.12)	−0.048 (−0.165, 0.068)	0.22	
Cognitive	1482	quartile 2	−0.114 (−0.228, −0.001)	−0.065 (−0.188, 0.058)	0.06	3431.3
		quartile 3	−0.045 (−0.162, 0.072)	0.023 (−0.101, 0.148)	0.06	
		quartile 4	−0.075 (−0.195, 0.045)	−0.088 (−0.214, 0.037)	0.06	
Motor	1482	quartile 2	−0.048 (−0.146, 0.05)	−0.062 (−0.167, 0.044)	0.33	2984.2
		quartile 3	0.028 (−0.073, 0.128)	−0.005 (−0.112, 0.103)	0.33	
		quartile 4	0.049 (−0.054, 0.152)	−0.051 (−0.158, 0.057)	0.33	
Language	1482	quartile 2	−0.083 (−0.211, 0.045)	−0.055 (−0.193, 0.083)	0.04	3786.8
		quartile 3	−0.1 (−0.231, 0.032)	0.076 (−0.064, 0.217)	0.04	
		quartile 4	−0.124 (−0.26, 0.011)	−0.053 (−0.194, 0.089)	0.04	
Socio-emotional	1482	quartile 2	−0.104 (−0.233, 0.025)	−0.05 (−0.189, 0.09)	0.05	3809.9
		quartile 3	−0.025 (−0.158, 0.108)	0 (−0.141, 0.142)	0.05	
		quartile 4	−0.081 (−0.217, 0.055)	−0.11 (−0.252, 0.032)	0.05	

[a] ECD scores obtained using the Caregiver Reported Early Development Instruments.
[b] Quartile 1 used as reference for all models.
[c] Fully adjusted model, with covariates: country, infant sex, maternal education and socioeconomic status.
[d] Akaike's Information Criterion (AIC) is a statistical measure used to compare models, balancing goodness of fit and model complexity, with lower AIC values indicating models that fit better the data.

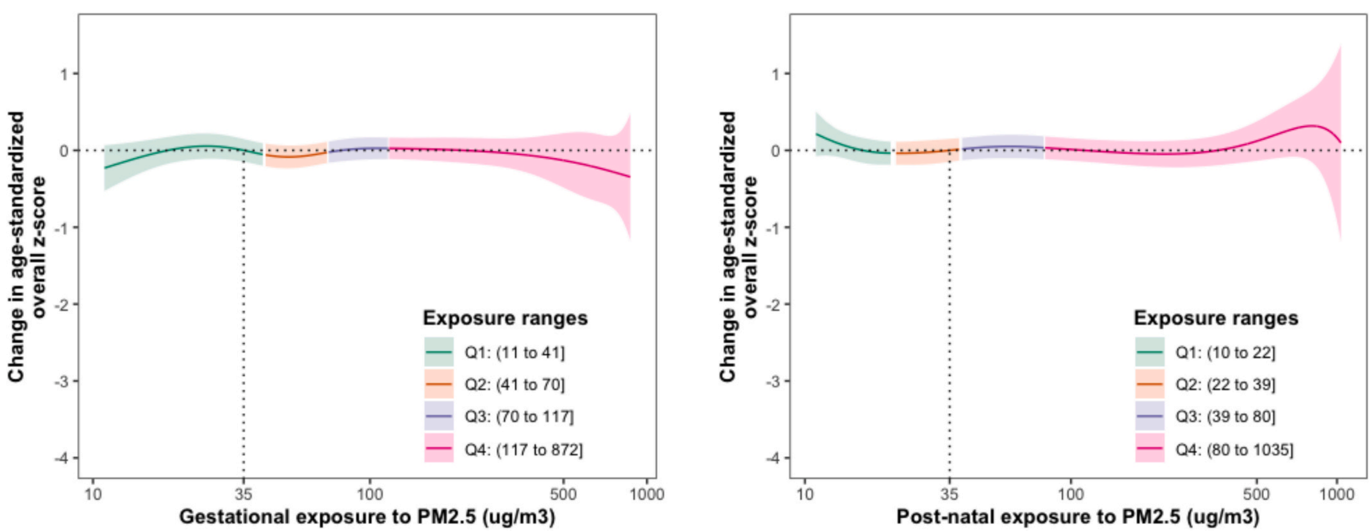

Fig. 3. Exposure-response relationships between gestational exposure to $PM_{2.5}$ and the age-standardized overall CREDI score. The models were constructed using cubic splines with 3 knots. The continuous line represents the change in z-score for each exposure value, relative to the WHO Interim Target 1 of 35ug/m3 for $PM_{2.5}$ (shown as a reference). Shaded regions represent the 95% confidence interval, with the color representing each quartile of the gestational exposure. Horizontal dashed line at 0 as a reference. Fully adjusted models, with covariates: country, infant sex, maternal education, and socioeconomic status.

neurodevelopmental outcomes (Chiu et al., 2016).

We found no consistent linear association between gestational or postnatal exposure to air pollution and overall or domain-specific age-standardized CREDI scores. We also did not find statistically significant positive associations in the quartile analyses. In non-linearity analyses we observed associations between postnatal exposures to $PM_{2.5}$ and higher, but not monotonically increasing, overall and all domain-specific CREDI scores compared to infants in the first quartile of exposure. However, the magnitude of the increase in CREDI scores for an increase in exposure to $PM_{2.5}$ was small. This null finding is similar to our exposure–response findings with prenatal exposures and fetal head circumference using ultrasound (Checkley et al., 2024), prenatal and postnatal $PM_{2.5}$ and severe child pneumonia during the HAPIN trial (McCracken et al., 2025), and respiratory outcomes in children (Shackelford et al., 2025); it is in contrast, however, with the exposure–response relationship reported for HAPIN primary outcomes for birth weight (Balakrishnan et al., 2023) and blood pressure (Pillarisetti et al., 2025).

Previous studies using the CREDI to evaluate ECD in descriptive research or program evaluations consistently report that infants around 12 months of age exhibit age-standardized scores close to the average of the CREDI reference population (Brentani et al., 2021; Hentschel et al., 2023; Leighton et al., 2023; Saleh et al., 2023). However, in our study, we observed significantly lower overall and domain-specific age-standardized scores compared to previously reported findings, except for overall and motor CREDI scores in India. Additionally, the scores in our study population differed between countries. While some of the variability could be due to differences in SES or maternal education attainment, we cannot rule out that in our settings the CREDI had a different performance than in the populations used to develop and standardize the evaluation tool (McCoy et al., 2021). Assessing developmental milestones can be challenging, as young children often lack fully developed verbal or social skills. As a result, evaluations typically depend on observations made by caregivers or trained assessors.

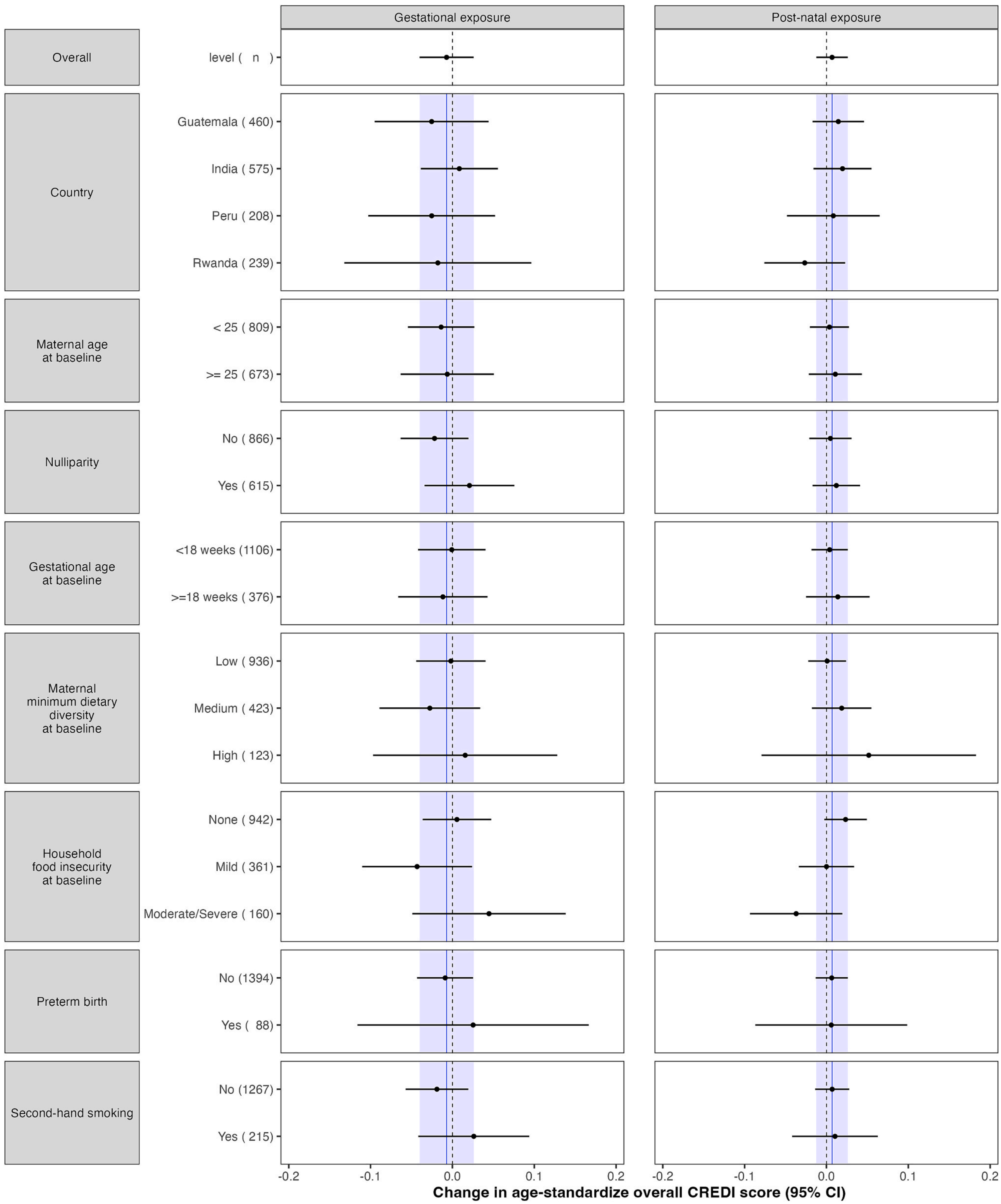

Fig. 4. Subgroup analyses for the association between gestational and postnatal exposure to $PM_{2.5}$, and the age-standardized overall CREDI score at 12 months. This figure shows the association for gestational and postnatal exposure to $PM_{2.5}$ across all participants, and within the specified subgroups (rows), for each period of exposure (columns). The shaded area and solid vertical line represent the association for the overall study population, as a reference. Dashed line at 0 as a reference. Maternal minimum dietary diversity adapted from Food and Agriculture Organization of the United Nations Minimum Diet Diversity for Women. The Food and Agriculture Organization Food Insecurity Experience Scale was used to assess food insecurity during the previous 30 days. We modeled the associations between the exposures and the overall CREDI score using linear regression, adjusting for country, infant sex, maternal education, socioeconomic status, and secondhand smoke except for sub-group analysis by country. For subgroup analysis by country, we adjusted for infant sex, maternal education, and socioeconomic status and secondhand smoke. Here we present the change in score given an increase of one interquartile range, for each exposure period.

Although caregiver recall of a child's behavior and interpretation of questions may introduce biases, studies have examined the psychometric properties of the CREDI across diverse international settings, both during its development and in research applications. (Alderman et al., 2021, 2021; Altafim et al., 2020; Li et al., 2020; McCoy et al., 2018; Waldman et al., 2021). These evaluations suggest that the limitations mentioned above might have a limited effect on the CREDI, with evidence that after adjusting for common determinants of early child development like SES and caregiver education the test correlates well with the BSID (Alderman et al., 2021). We note that several characteristics between participants with and without missing outcomes were different (e.g. lower levels of secondary education, lower dietary diversity, higher household food insecurity, and higher rates of exposure to secondhand smoking in those assessed vs. those not assessed), suggesting selection bias. This differential missingness may have introduced bias if these covariates affected maternal reports of child behaviors at the 12-month assessment. This limitation should be considered when interpreting these findings.

The strengths of this study include the use of a randomized controlled trial design, the inclusion of children drawn from four global regions, which enhances the generalizability of the findings; high retention rates and comprehensive data collection; as well as near-universal fidelity and adherence within the intervention group. Our study has several limitations. First, while the study benefited from the exposure assessment methods used in the HAPIN trial, with the ability to differentiate between gestational and postnatal exposure, the design of the study did not allow us to consider the possible effects of exposure earlier in pregnancy or even before conception. Second, the use of indirect or reconstructed methods for exposure assessment may have resulted in non-differential misclassification, leading to inaccuracies in estimating actual exposure levels, thus reducing our ability to detect a relationship between exposures and ECD outcomes in exposure–response analyses. Third, some of the interviews were conducted on the phone during the COVID pandemic, which may have reduced data quality. Finally, while we pilot-tested the instruments, trained local fieldworkers prior to deployment, and implemented quality assurance measures during the study, we did not validate the CREDI to assess its comparability with gold-standard methods (e.g., BSID) or examine the potential impact of social desirability bias. While these limitations restrict our ability to determine whether the discrepancies observed compared to prior research are substantive or the result of bias or measurement error, bias would be uniform across intervention and control groups.

Notwithstanding these limitations, the findings of this study suggest that, while reducing air pollution is crucial for overall health, a clean cooking intervention may not be sufficient by itself to significantly influence developmental scores during the first year of life. This highlights the complexity of ECD and underscores the need for multifaceted intervention strategies that simultaneously address environmental, nutritional, and socio-economic factors, which is in line with recommendations from UNICEF's Vision for Every Child for ECD (Aguayo and Britto, 2024). Future analyses of HAPIN participants, including evaluation of development in children ages 2 through 5, are currently underway. These may be better equipped to identify differences associated with intervention effects and measured air pollution exposures.

5. Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the author(s) used ChatGPT Enterprise in order to modify the graphical abstract. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

6. Trial registration

This study was registered at ClinicalTrials.gov (NCT02944682) on October 24, 2016.

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CRediT authorship contribution statement

Lisa M. Thompson: Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Conceptualization. **Oscar de León:** Conceptualization, Data curation, Formal analysis, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Sheela Sinharoy:** Writing – review & editing, Methodology, Investigation. **Viviane Valdes:** Writing – review & editing, Validation, Supervision, Methodology, Investigation. **Seema Das:** Writing – review & editing, Visualization, Software, Formal analysis, Data curation. **Vigneswari Aravindalochanan:** Writing – review & editing, Supervision. **Ajay Pillarisetti:** Writing – review & editing, Methodology, Data curation. **Shirin Jabbarzadeh:** Writing – review & editing, Validation, Resources, Project administration, Data curation. **Kalpana Balakrishnan:** Writing – review & editing, Project administration, Investigation. **Anaite Diaz-Artiga:** Writing – review & editing, Supervision, Project administration. **John P. McCracken:** Writing – review & editing, Project administration, Data curation. **Ghislaine Rosa:** Writing – review & editing, Project administration. **Gurusamy Thangavel:** Writing – review & editing, Project administration. **Sankar Sambandam:** Writing – review & editing, Investigation. **Krishnendu Mukhopadhyay:** Writing – review & editing, Investigation. **Naveen Puttaswamy:** Writing – review & editing, Data curation. **Marilu Chiang:** Writing – review & editing, Investigation. **Florien Ndagijimana:** Writing – review & editing, Investigation. **Amy E. Lovvorn:** Writing – review & editing, Project administration. **Kyle Steenland:** Writing – review & editing, Methodology, Formal analysis. **Dana Boyd Barr:** Writing – review & editing, Investigation, Conceptualization. **Usha Ramakrishnan:** Writing – review & editing, Methodology, Investigation. **William Checkley:** Writing – review & editing, Project administration, Methodology, Investigation, Funding acquisition. **Jennifer Peel:** Writing – review & editing, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Thomas Clasen:** Writing – review & editing, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2026.110350.

Data availability

Data will be made available on request.

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