Environmental Research 212 (2022) 113265

Contents lists available at ScienceDirect

Environmental Research

journal homepage: www.elsevier.com/locate/envres

Biomass fuel use for cooking in Nepalese families and child cognitive abilities, results from a community-based study

Ingrid Kvestad [a,b], Ram K. Chandyo [c], Catherine Schwinger [d], Suman Ranjitkar [e], Mari Hysing [f], Manjeswori Ulak [d,e], Merina Shrestha [e], Laxman Shrestha [e], Tor A. Strand [b,d,*]

[a] Regional Centre for Child and Youth Mental Health and Child Welfare, NORCE Norwegian Research Centre, Bergen, Norway
[b] Department of Research, Innlandet Hospital Trust, Lillehammer, Norway
[c] Department of Community Medicine, Kathmandu Medical College, Kathmandu, Nepal
[d] Centre for Intervention Science in Maternal and Child Health, Centre for International Health, Department of Global Public Health and Primary Care, University of Bergen, Bergen, Norway
[e] Department of Child Health, Institute of Medicine, Tribhuvan University, Kathmandu, Nepal
[f] Department of Psychosocial Science, Faculty of Psychology, University of Bergen, Bergen, Norway

ARTICLE INFO

Keywords:
Biomass fuel use for cooking
Household air pollution
Child cognition
WPPSI-IV
Low to middle income countries
Community-based sample
Cohort design

ABSTRACT

Background: Biomass fuel use for cooking is widespread in low to middle income countries. Studies on the association between biomass fuel use and cognitive abilities in children are limited.
Objective: To examine the association between biomass fuel use for cooking and cognitive abilities in Nepalese children at 4 years of age.
Methods: In a cohort design we have information on biomass fuel use in the households of 533 children in infancy and cognitive abilities when they were 4 years old from a community-based sample. Cognitive abilities were measured by the Wechsler Preschool and Primary Scale of Intelligence, 4th edition (WPPSI-IV) and the NEPSY-II. We examined the associations between biomass fuel use and scores on the WPPSI-IV Full-Scale IQ (FSIQ) (primary outcome), and WPPSI index and NEPSY-II subtest scores in multiple linear regression models. The associations were also examined in predefined subgroups.
Results: Ninety-nine (18.6%) of the families used biomass fuel for cooking. Children in these families had lower mean FSIQ than children in families with no biomass use (83.3 (95%CI 81.7, 85.0) vs. 85.3 (95%CI 84.5, 86.0)), with a mean difference of −2.2 (95%CI -3.9, −0.5) adjusting for demographics and socio-economic status. The association between biomass fuel use and cognitive abilities was strongest in subgroups of children from households with more than three rooms, with separate kitchen and bedroom, and with higher wealth-score. These interactions were significant for number of rooms in the home ($p = 0.04$), if the household had separate bedroom and kitchen ($p = 0.05$), and for the wealth-score ($p = 0.03$).
Conclusion: Biomass fuel use for cooking in Nepalese families was associated with lower overall cognitive abilities at 4 years. Uncertainties include exposure misclassification and unmeasured confounding. The associations between biomass fuel use and neurodevelopment in children needs further investigation with more precise measurements of the exposure.

1. Introduction

Biomass as cooking fuel is widely used in low to middle income countries (Bruce et al., 2000; Burning, 2016). The use of biomass fuel such as wood, coal, and other solid fuels as an energy source for cooking results in pollutants such as carbon monoxide (CO) and particular matter (PM) leading to household air pollution (HAP) (Smith et al., 2014; Mannucci and Franchini, 2017). HAP being one of the major risk factors in the 2019 Global Burden of Diseases, Injuries and Risk Factors Study (Murray et al., 2020), contributes to a high burden of mortality and morbidity in vulnerable populations, in particular among women and young children (Burning, 2016; Fullerton et al., 2008).

Well-described adverse health effects linked to HAP include acute respiratory infections, chronic obstructive pulmonary disease,

* Corresponding author. Centre for International Health, Department of Global Public Health and Primary Care, University of Bergen, Bergen, Norway.
E-mail address: Tor.Strand@uib.no (T.A. Strand).

https://doi.org/10.1016/j.envres.2022.113265
Received 6 December 2021; Received in revised form 4 April 2022; Accepted 5 April 2022
Available online 30 April 2022

pulmonary tuberculosis, cataracts, low birth weight, perinatal and infant mortality, nasopharyngeal and laryngeal cancer, and lung cancer (Bruce et al., 2000; Smith et al., 2014; Fullerton et al., 2008). Although not conclusive, there is support in the literature for the adverse effects of both pre- and postnatal *outdoor* air pollution exposure on child neurodevelopment (Suades-Gonz á lez et al., 2015; Clifford et al., 2016; Bansal et al., 2021). Studies on *indoor* air pollution and child neurodevelopment are limited, however. Recent observational studies have demonstrated that exposure to biomass fuel use was associated with lower cognitive scores in Indian children (Brabhukumr et al., 2020), and that children exposed to biomass fuel use were more likely to be developmentally delayed compared to unexposed children using the UNICEF Multiple Indicators Cluster Survey in a sample of Ghanaian children (Nazif-Munoz et al., 2020). In Guatemalan school children, pre- and postnatal exposure to woodsmoke was negatively associated with neurodevelopment (Dix-Cooper et al., 2012).

Globally, there has been a general decline in the use of biomass fuel for heating and cooking (IEA, 2017), but biomass use is still common among the most disadvantaged populations. In Nepal, the 2016 national survey showed that more than two-thirds of households used biomass fuel for cooking (Ministry of Health, Nepal, 2017). According to World Health Organization (WHO) guidelines, the air quality of Nepalese household has been evaluated to be poorer than acceptable levels (WHO, 2014). This is likely due to lack of separate rooms for cooking and poor ventilation (Bartington et al., 2017; Devakumar et al., 2014). Following malnutrition, air pollution was the second most important risk factors for death and disabilities in Nepal in 2019 (Murray et al., 2020; Institute for Health Metrics and Evaluation, 2021).

The exact mechanistic pathways for air pollution on neurodevelopment are uncertain, but studies have focused on PM exposure and in particular $PM_{2.5}$, (Babadjouni et al., 2017; Costa et al., 2020). The WHO has an indoor air standard for $PM_{2.5}$ of 25 μg/m^3 (WHO, 2014). In a study from 82 households in the Bhaktapur district of Nepal, the mean $PM_{2.5}$ concentrations were 656 μg/m^3, 169 μg/m^3, 101 μg/m^3 and 80 μg/m^3 in households using biomass, kerosene, gas, and electric stoves respectively (Pokhrel et al., 2015). Compared with electric stoves, the use of biomass stoves was associated with a 65% increased indoor $PM_{2.5}$ concentration.

Being among the least developed countries in the world, more than one-third of the Nepalese population live below the poverty line. The life of vulnerable children is characterized by multiple risks such as low birth weight (Ahammed et al., 2020), micronutrient deficiencies (Ulak et al., 2016), and stunted growth (McCoy et al., 2016). Related to these risks, estimates from 2016 suggest that more than one third of preschool children in Nepal fail to meet basic developmental milestones, and efforts to identify modifiable risk factors for poor neurodevelopment are called for (McCoy et al., 2016). The primary objective of the current study was to examine the association between reported use of biomass fuel for cooking during infancy and overall cognitive abilities as measured by the Wechsler Preschool and Primary Scale of Intelligence, 4th edition (WPPSI-IV) full scale IQ (primary outcome) in a Nepalese child cohort when the children were 4 years old. Secondary objectives were to examine the extent to which the biomass fuel use was associated with specific cognitive functions as measured by WPPSI-IV index scores and NEPSY subtests (secondary outcomes). In subgroup analyses, we also explored whether the potential association between biomass fuel use and cognitive abilities was modified by certain baseline variables reflecting growth, socioeconomic status, and housing conditions.

2. Materials and methods

2.1. Study design and population

Data in these analyses stem from a follow up of a cohort of Nepalese children originally participating in a community-based randomized double-blind placebo-controlled nutrition trial (RCT) (Strand et al., 2017). Following the completion of the clinical trial, we have continued to follow the cohort yearly until their 4th birthday (Ulak et al., 2022). In the current study, we used data on cooking fuel in the families collected at the enrollment for the original trial when the children were 6–11 months and data on cognitive abilities when the children were 42–47 months. From this follow up, we have data from 533 children of the original 600 enrolled children (89%). The main reason for lost-to follow up was refusal and migration.

The study setting was Bhaktapur municipality, one of the most densely populated municipalities in Nepal (11,430 inhabitants/km^2) (Central Bureau of Statistics, 2021). Bhaktapur is predominantly inhabited by the Newar ethnic group, but also by immigrants mostly working in carpet factories. The main livelihood is agriculture, with small-scale self-owned businesses and daily wage labor also being important sources of income. Women in the municipality are primarily engaged in household work and agriculture, but some also in self-owned businesses, daily wage work, services and in carpet work. Most births (96%) occur at health centers and about half of the families live in joint households (Shrestha et al., 2014). The climate is characterized by a warm and wet monsoon season (June–September) and a cold and dry winter season (December–February). The average annual temperature is 16.0 °C and about 2596 mm of rain falls annually (CLIMATE-DATA.org 2022). In the households, energy is generally used for cooking (Bates et al., 2013), but could also to a more limited extent be used for heating during the winter (KC and Nakarmi, 2021). In traditional households in the study area, the kitchen is often placed on the top floor separated from the rest of the house (Supplemental Figure S1). A typical characteristic of rented homes in the area is one-to-two-room households where the kitchen also is used for sleeping purpose. In most kitchen areas, ventilation is handled by separate holes in the roof or through opening doors and/or windows (Bates et al., 2013). The outdoor air quality in the district has been estimated to be poor as measured by 24 h $PM_{2.5}$ concentrations exceeding the standard set by WHO (WHO, 2014). The poor ambient air quality is most likely explained by a major highway and brick kilns on the outskirt of the municipality, as well as the dense households and the communal firing for the traditional pottery production (Pokhrel et al., 2015).

In the parent RCT, with enrollment from April 2015 until February 2018, we included 600 mildly stunted children (i.e, length for age z-score < -1) to receive 2–3 recommended daily allowances of vitamin B12 or placebo for 12 months to measure the effect on neurodevelopment, growth, and hemoglobin concentration. Children were excluded if they took (or planned to take) supplements that contained vitamin B12; had a severe systemic illness requiring hospitalization; if they were severely malnourished (weight for length z-score < -3); were severely anemic (hemoglobin concentration <7 g/dL); or had ongoing infections that required medical treatment. At enrollment we collected information regarding socioeconomic status, demographics, and housing conditions, in addition to measures of growth, morbidity, and neurodevelopment. We found no effect of the vitamin B12 on the neurodevelopmental outcomes in the orginial trial (Strand et al., 2020; Ulak et al., 2022).

The study received ethical clearance from the Nepal Health Research Council (NHRC, #233/2014, #73/2017) and from the Regional Committee for Medical and Health Research Ethics (REC # 2014/1528) in Norway. We obtained written informed consent from caregivers after providing thorough information on the study procedures both for the trial and for the follow-up.

2.2. Variables

At enrollment to the original trial, weight and length were measured at the clinic with portable electronic scales (Salter/HoMedics Group, UK and seca, Germany) and infantometers. All anthropometric measurements were converted to Z-scores with reference to the WHO Child Growth Standards (WHO, 2006). Stunting was defined as a height for age z-score < -2 and underweight as a weight for age z-score < -2. Birthweight was retrieved from hospital records and low birthweight was defined as <2500 g.

Caregivers were asked questions about child, family, and household characteristics. Separate kitchen and bedroom in the household was defined by whether the kitchen room also was used for sleeping purpose. Family type was defined as nuclear if only the parents and the child were living together, and joint if more family members from two or more generations lived in the household. As part of these enrollment procedures, parents were specifically asked about main fuels used for cooking in the household, such as firewood, saw dust, straw, cow dung, rice husk, kerosene, other gas, electricity, or others. We defined biomass fuel as firewood, saw dust, straw, and rice husk for the current analyses. Kerosene was decided a priori not to be defined as biomass fuel. We only collected information on the main source for cooking, even from families that used multiple types in the household. We did not systematically collect information on secondary fuel sources or the main source for heating. As a measure of socioeconomic status, we used the WAMI-index as suggested by Psaki and colleagues (Psaki et al., 2014). The WAMI-index is calculated based on variables on safe drinking water and sanitation, mother's education, income, and the availability of household assets (Psaki et al., 2014). We did not have information on household income and adapted the calculation to include only the other components (for details, see Supplementary Table S1). The WAMI-index ranges from 0 to 1, with a higher value indicating a better status. We used this index as a continuous variable. Indoor smoking was answered yes/no.

2.3. Neurodevelopmental assessments

Cognitive abilities were measured by the Wechsler Preschool and Primary Scale of Intelligence, 4th edition (WPPSI-IV) and the Developmental NEuro PSYchological Assessment 2nd edition (NEPSY-II) when the children were 42–47 months (approximately 4 years). WPPSI-IV is a widely used test to measure intellectual abilities in children from 2 years and 6 months to 7 years and 3 months (Wechsler, 2012). In the present study, six subtests were included: Information, Receptive Vocabulary, Block Design, Picture Memory, Object Assembly and Zoo Locations. These subtests were used to generate the Full-Scale IQ (FSIQ), the Verbal comprehension index (VCI), the Visuospatial index (VSI), and the Working memory index (WMI). The FSIQ and the index scores (all with a mean (SD) of 100 (WHO, 2014)) were calculated based on US norms (Wechsler, 2012).

NEPSY-II is a neuropsychological cognitive assessment tool that can be tailored for children aged 3–16 years (Korkman et al., 1998). The NEPSY-II consists of 32 subtests in six functional domains. The following three age-appropriate subtests were administered in this study: Affect Recognition, Statue, and Geometric Puzzles. These are from the Social Perception, Executive Functioning and Visual-Spatial Processing domains, respectively. We used raw scores and scaled scores (mean (SD) of 10 (3)) calculated based on US norms (Brooks et al., 2009). Prior to the study, three psychologists were trained by an experienced senior psychologist, and standardization exercises were performed in 20 children with the requirement to reach excellent agreement with the expert rater (Intra class correlations (ICC) > 0.90). During the study period, 10 percent of the assessments were double scored by the expert rater in a randomized manner, reaching an ICC of >0.98.

2.4. Statistical analysis

Data are presented as numbers and percentages (%) for categorical variables or means and standard deviations (SD) for continuous variables. We graphically present the distribution of the WPPSI-IV FSIQ separately for the group of children living in homes with biomass fuel use or not in smoothed density plots using univariate kernel density estimation (kdensity in Stata). To estimate the association between biomass fuel use and cognitive abilities, we used linear regression models with biomass fuel use as exposure (0 = no biomass fuel use, 1 = biomass fuel use), the WPPSI-IV FSIQ as the primary outcome, and the WPPSI-IV index scores and NEPSY-II subtest scores as secondary outcomes. The outcome variables were normally distributed, and no transformation was necessary. For each outcome, we built four separate statistical models. Model 1 is the crude analysis. Model 2 includes the following predefined demographic and socio-economic (SES) variables based on their theoretical importance for the outcomes (Sania et al., 2019; Julvez et al., 2021), and the availability in the study: WAMI-score, age, time of measurement, sex, maternal age, paternal education and occupation, and indoor tobacco smoking. In model 3, we additionally included anthropometric variables, i.e., birthweight and baseline stunting and underweight. These variables were not included in model 2 since these could be in the causal pathway between the exposure variable (biomass fuel use) and the outcome (cognitive abilities). Based on the observed baseline differences (Table 1) we also included a model 4 with the following variables included: maternal occupation, joint or nuclear family, own or rented house, number of rooms in the home, and

Table 1
Child and family demographics in 531 Nepalese children stratified on biomass exposure.

N	Biomass	No Biomass
	99 (18.6%)	432 (81.4%)
Cooking fuel		
Firewood/saw dust/straw/rice husk	99 (18.6%)	
Gas		418 (78.7%)
Kerosene		6 (1.1%)
Electricity		8 (1.5%)
Child characteristics		
Age in months at enrollment, mean (SD)	8.0 (1.8)	8.0 (1.8)
Age in months at neurodevelopment assessment, mean (SD)	43.8 (1.9)	43.9 (1.9)
Male	56 (56.6%)	216 (50%)
Born with low birthweight	20 (20.2%)	85 (19.7%)
Exclusively breastfed less than 3 months	59 (59.6%)	232 (53.7%)
Stunted at 6–11 months of age	40 (40.4%)	135 (31.3%)
Underweight at 6–11 months of age	21 (21.2%)	82 (19.0%)
Family characteristics		
Maternal age in years at enrollment, mean (SD)	28.3 (4.5)	27.5 (4.6)
Mothers who completed secondary school	35 (35.4%)	205 (47.2%)
Mothers who work	31 (31.3%)	194 (44.9%)
Fathers who completed secondary school	33 (33.3%)	196 (46.2%)
Fathers who work	95 (96.0%)	422 (97.7%)
WAMI-index, mean (SD)	0.64 (0.1)	0.62 (0.2)
WAMI-index < 33rd percentile	20 (20.2%)	142 (32.9%)
Living in joint family	76 (76.8%)	197 (45.6.0%)
Living in rented house	25 (25.3%)	213 (49.3%)
Family owns land	68 (68.7%)	198 (45.8%)
Family household has >3 rooms	63 (63.6%)	183 (42.4%)
House with kitchen and bedroom in separate rooms	68 (68.7%)	214 (49.5%)
Indoor tobacco smoking	63 (63.6%)	208 (48.2%)

Numbers are N (%) if not otherwise stated.

separate kitchen and bedroom. Since kerosene use also have been linked to adverse health outcomes (Bates et al., 2018) we performed sensitivity analyses with the primary outcome, removing the six participants reporting to use kerosene as cooking fuel.

We repeated the regression analyses with the primary outcome (WPPSI-IV FSIQ) in the following pre-defined subgroups: Birthweight (<2500 g vs. ≥ 2500 g), exclusive breastfeeding (<3 months vs. ≥ 3 months), stunting (length-for-age < -2 SD vs. ≥ −2 SD), underweight (weight-for-age < -2 SD vs. ≥ −2 SD), WAMI-score (<33rd percentile vs. ≥ 33rd percentile), number of rooms in the house (<3 rooms vs. ≥ 3 rooms) and separate kitchen and bedroom (no vs. yes). These subgroups were selected based on the potential for increased vulnerability for the biomass fuel exposure. The subgroup analyses were adjusted for the same covariates as in model 2. Post hoc, we repeated these subgroup analyses with the secondary outcomes; WPPSI-IV index scores (VCI, VSI and WMI) as outcomes. We also measured whether the above-mentioned subgrouping variables modified the association between biomass fuel use and cognitive abilities by including interaction terms in multiple linear regression models. All data analyses were done using Stata 16 (StataCorp LLC, College Station, TX).

3. Results

The distribution of baseline demographics in the total enrolled sample (N = 600) and the current study sample (N = 533) is shown in Supplementary Table S2. In the total sample of 533 children, two were excluded due to very low scores on the cognitive assessments and related diagnoses.

Demographics, SES, and housing conditions by biomass fuel use in the households for the 531 children are shown in Table 1. Of the families, 99 (18.6%) reported using biomass fuel such as firewood, saw dust, straw, or rice husk for cooking. In the 432 families that did not use biomass fuel for cooking, the majority used gas (78.7%) and only a small proportion (approximately 1% each) used kerosene and electricity. The children in both groups were on average 44 months at the time of assessment, and 56.6% and 50% of the children were male in the biomass fuel use and no biomass fuel use group respectively. At 6–11 months, 40% of the children in the biomass fuel use group were stunted, while 31% were stunted in the no biomass fuel use group. Twenty % of the families in the biomass fuel group had a WAMI-score in the lowest 33rd percentile, while 33% in the no biomass fuel group were in the lowest 33rd percentile.

Children in the biomass fuel group had on average lower WPPSI FSIQ scores than children in the no-biomass fuel group (mean (95%CI): 83.3 (81.7, 85.0)) and 85.3 (84.5, 86.0)) (Fig. 1, Table 2). This difference was significant when adjusting for demographics, SES, and tobacco smoking (mean difference (95%CI) of −2.2 (−3.9, −0.5) (model 2). Additional adjustments for anthropometry (model 3) and further demographics and housing conditions (model 4) did not substantially alter the strength and precision of the estimates (Table 2).

For the secondary outcomes, there were no significant mean differences between the groups (Tables 2 and 3), except for a significant mean difference (95%CI) of −3.0 (−5.9, −0.04) for the WMI in the fully adjusted model (model 4) (Table 2). In sensitivity analyses removing the participants that reported using kerosene, regression analyses with the primary outcome did not result in alterations to the estimates.

The association between biomass fuel use and the FSIQ was modified by the number of rooms in the home (p = 0.04), if the household had separate bedroom and kitchen (p = 0.05) and the WAMI-score (p = 0.03). The association between biomass fuel use and FSIQ in subgroups are depicted in Fig. 2. The plot shows that the associations between biomass fuel use and cognitive abilities is highest in the subgroups consisting of children from households with more than three rooms in the household, with separate kitchen and bedroom, and in children from families with a WAMI-index above 33rd percentile. These associations were confirmed using the WMI and VCI scores of WPPSI-IV, but not the VSI score as outcomes (supplemental Figure S2).

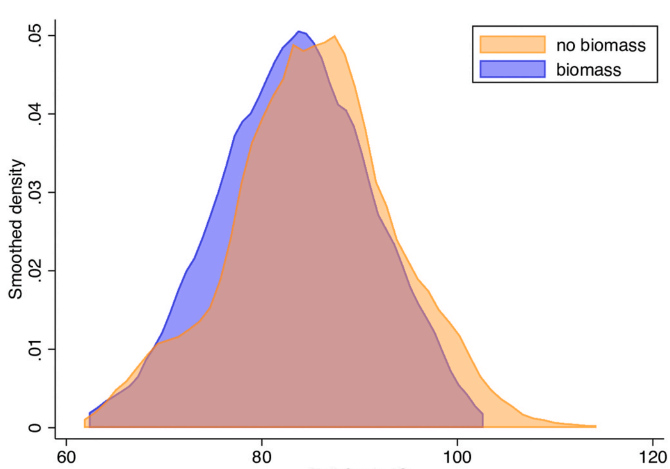

Fig. 1. Distribution of WPPSI Full-Scale IQ in Nepalese children in families with biomass fuel use for cooking and in families with no biomass fuel use. Legend: Smoothed density plots using univariate kernel density estimation.

Table 2
Mean (SD) of the Wechsler Preschool and Primary Scale of Intelligence, 4th edition (WPPSI-IV) full scale IQ and index scores and mean differences between the scores in children living in families with biomass fuel use for cooking compared to no biomass fuel use.

WPPSI-IV	Biomass Mean (SD)	No biomass Mean (SD)		Mean diff.	95%CI
Full Scale IQ	83.3 (7.5)	85.3 (8.3)	model 1 (crude)	−1.9	−3.7, −0.1
			model 2[a]	−2.2	−3.9, −0.5
			model 3[b]	−2.0	−3.7, −0.3
			model 4[c]	−2.1	−4.0, −0.2
Verbal comprehension index	83.1 (6.7)	84.4 (7.9)	model 1 (crude)	−1.3	−3.0, 0.4
			model 2	−1.5	−3.2, 0.1
			model 3	−1.3	−2.9, 0.4
			model 4	−1.6	−3.3, 0.2
Visuospatial index	85.0 (7.2)	85.7 (8.7)	model 1 (crude)	−0.9	−2.7, 0.9
			model 2	−1.1	−2.8, 0.7
			model 3	−1.0	−2.8, 0.7
			model 4	−0.8	−2.6, 1.0
Working memory index	102.1 (12.6)	104.1 (12.9)	model 1 (crude)	−2.0	−4.8, 0.8
			model 2	−2.6	−5.4, 0.2
			model 3	−2.3	−5.2, 0.5
			model 4	−3.0	−5.9, −0.04

Linear regression models with biomass use = 1 vs. no biomass use = 0.
[a] Adjusted for age, sex, time of measurement, maternal age, paternal education, and occupation, WAMI-index and indoor tobacco smoking.
[b] As model 1 and also adjusted for birthweight, height-for-age z-score and weight-for age z-score.
[c] As model 1 and also adjusted for maternal occupation, joint or nuclear family, own or rented house, number of rooms in the home, and separate kitchen and bedroom.

Table 3
Mean (SD) of the NEPSY-II subtest scores and mean differences between the scores in children living in families with biomass fuel use for cooking compared to no biomass fuel use.

NEPSY-II subtests	Biomass Mean (SD)	No biomass Mean (SD)		Mean diff.	95%CI
Geometric puzzles	9.0 (2.6)	9.1 (2.9)	model 1 (crude)	0.04	−0.6, 0.7
			model 2[a]	−0.1	−0.7, 0.6
			model 3[b]	−0.04	−0.6, 0.6
			model 4[c]	0.01	−0.6, 0.6
Affect recognition	8.0 (1.7)	8.2 (2.0)	model 1 (crude)	−0.2	−0.6, 0.3
			model 2	−0.2	−0.6, 0.2
			model 3	−0.2	−0.6, 0.3
			model 4	−0.3	−0.7, 0.3
Statue	9.8 (3.4)	10.3 (3.2)	model 1 (crude)	−0.5	−1.2, 0.2
			model 2	−0.5	−1.2, 0.3
			model 3	−0.4	−1.2, 0.3
			model 4	−0.5	−1.2, 0.3

Linear regression models with biomass use = 1 vs. no biomass use = 0.
[a] Adjusted for age, sex, time of measurement, maternal age, paternal education, and occupation, WAMI-index and indoor tobacco smoking.
[b] As model 1 and also adjusted for birthweight, height-for-age z-score and weight-for age z-score.
[c] As model 1 and also adjusted for maternal occupation, joint or nuclear family, own or rented house, number of rooms in the home, and separate kitchen and bedroom.

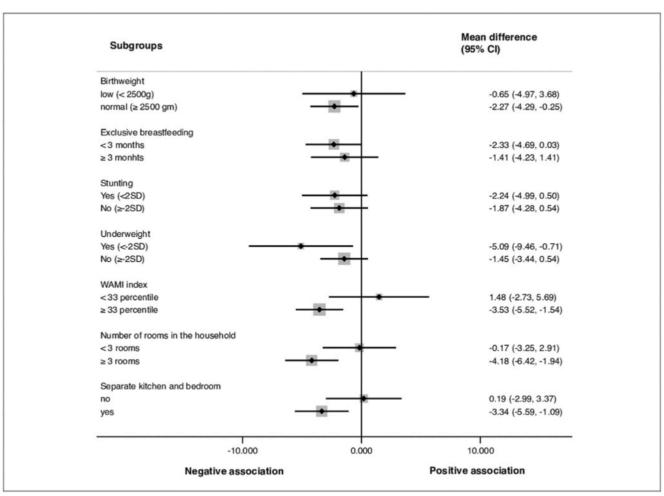

Fig. 2. The association between biomass fuel use and WPPSI-IV Full scale IQ (FSIQ) in selected subgroups.
Legend: The figure depicts mean difference in FSIQ comparing biomass fuel (=1) to no biomass fuel (=0) use. Regression models are adjusted for age, sex, time of measurement, maternal age, paternal education, and occupation, WAMI-score, and indoor tobacco smoking.

4. Discussion

In the current study, we examined the relationship between biomass fuel use for cooking and cognitive abilities in children living in a densely populated area of Nepal. Cognitive abilities as measured by WPPSI-IV full scale IQ at 4 years, were the predefined primary outcome of the analysis. Close to 18 percent of the families reported using biomass fuel for cooking. After adjusting for demographic factors and SES, we find that children living in families using biomass fuel for cooking had an estimated 2.2 lower IQ scores than children in families with no biomass fuel use. The current results mirror findings from the few previous studies in this field suggesting an adverse impact of biomass fuel use on child cognition (Brabhukumr et al., 2020; Nazif-Munoz et al., 2020; Dix-Cooper et al., 2012). Hence, the current results contribute to the evidence base suggesting that exposure to HAP is associated with lower cognitive scores in children.

The number of families reporting to use biomass fuel for cooking in the current study is lower than what is reported by the 2016 national demographic survey suggesting that more than two-third of households in Nepal use biomass fuel (Ministry of Health, Nepal, 2017). The national demographic survey covers the whole of Nepal including all the rural areas in which a much higher proportion of people use biomass fuel. At the same time, for various reasons which probably includes the global effort to reduce the exposure to biomass fuels and the increased standard of living in the community, the use of such fuels decreases. The fuel distribution in the current study is strikingly different from that of previous studies in the area, such as a study that was undertaken between 2006 and 2008 where approximately 25% reported using kerosene as primary cooking fuel and 20% electricity (Bates et al., 2013). Both are considerably above what was reported in the current study (approximately 1% for each). In the previous study, reported biomass fuel use was 26% which is a little more than in our results and associated with acute lower respiratory infections (ALRI). The most striking link, however, was with kerosene use, where the risk of ALRI increased considerably with $PM_{2.5}$ concentrations (Bates et al., 2018). In our sensitivity analyses, removing children from households using kerosene did not alter our results which is expected given the low number of families that reported kerosene use for cooking.

A secondary objective with the current study was to explore specific cognitive domains related to the biomass fuel use. In both the main and post hoc subgroup analyses, our findings suggest that the association between the FSIQ and biomass fuel use is driven by the index scores reflecting working memory and verbal comprehension, but not visuospatial abilities as shown in the supplemental figure S2. The analyses with the NEPSY-II subtests as outcomes confirm that visuospatial abilities (the Geometric puzzle test) are not related to biomass fuel use, and moreover, suggests that the cognitive domains of executive functioning (the Statue test) and social perception (the Affect recognition test) is not affected by HAP. Associations between HAP and working memory were also found among Guatemalan school children and European children (Dix-Cooper et al., 2012; Julvez et al., 2021), and there is some support for the adverse effects of air pollution exposure on short term memory abilities in animal studies (Allen et al., 2017). Moreover, studies from Ghana and India reported on associations within the verbal domain, also in accordance with the current findings (Brabhukumr et al., 2020; Nazif-Muñoz et al., 2020). Notably, in the study among Guatemalan children, prenatal exposure was associated with visuospatial abilities (Dix-Cooper et al., 2012) which is in contrast to our findings demonstrating the complexity of studies on early exposure and the developing brain. The period from conception until approximately the 2nd birthday is a period of massive and finely tuned brain development in which the developing brain is considered to be vulnerable to adverse influences (Fox et al., 2010). In this period, adding to the vulnerability, the central nervous system is in particular sensitive to the adverse effects from the neurotoxic exposure since the blood-brain barrier is not fully developed (Bellinger, 2018). Numerous studies have examined the underlying mechanisms involved in air pollution exposure and the brain, but the specific neurotoxicological mechanisms remain unclear (Allen et al., 2017). Potential mechanisms include oxidative stress and inflammation, alterations in dopamine and glutamate neurotransmitter systems, and changes in synaptic plasticity and structures (Allen et al., 2017;

Bellinger, 2018). Our findings suggesting associations in the working memory and verbal comprehension domains of cognitive abilities are interesting, but preliminary. More studies are needed to characterize the specific impact from HAP exposure on the central nervous system.

In subgroup analyses, we explored potential drivers of the association between the biomass fuel use and cognitive abilities according to the growth status of the children, SES of the families and household conditions. While these analyses yielded no significant findings based on whether the child was stunted or not, there were associations between biomass fuel use and cognitive abilities in children not exclusively breastfed for more than 3 months and in children who were underweight when they were 6–11 months. Findings could be related to that due to increased vulnerability, children in these subgroups were less protected to the biomass fuel exposure and hence the neurotoxicological impact on the developing brain was greater. Unexpectedly, the associations between biomass fuel use and cognitive abilities were stronger among groups characterized by higher SES, such as with more rooms in the home and being wealthier. It is important to underline the uncertainty related to these findings due to the small sample size in some of the subgroups, the many covariates included in the regression models, and the multiple testing with only some of the comparisons being statistically significant. Taking these uncertainties into account, however, the findings could suggest that children from lower socio-economic circumstances may be exposed to other and more extreme biological and psychosocial risk factors overshadowing the effect of HAP, and thus rendering these children's neurodevelopment relatively less susceptible to the adverse impact of HAP exposure. This is confirmed by the distribution plot showing that it is in the right-hand tail of the distribution we see a difference between the exposure groups.

An important question is the timing of the toxic exposure in the developing brain and the potential differential impact depending on the period of exposure (Allen et al., 2017). In the current study we collected information on biomass fuel use when the children were 6–11 months old. Still, we do not have information on the specific timing of the HAP exposure. Since women traditionally are those involved in household activities and at the same time have the main responsibility for the children, women and children are those mostly exposed to the biomass fuel in low-resource settings (Bruce et al., 2000). The biomass fuel exposure in the current study children could therefore have occurred during pregnancy or after birth, or both. A limitation to the current study, is that this is impossible to disentangle. Future studies should incorporate the issue of timing of exposure to identify periods in which the developing brain is particular susceptible to the neurotoxic exposure from HAP.

The anthropometric measures of being born at low birthweight, and being stunted and underweight, were considered as being in the causal pathway given the potential association with HAP and growth (Kyu et al., 2009) as well as the well-known association between the growth variables and neurodevelopment (Sudfeld et al., 2015). Notably, there were no differences in the proportion born with low weight at enrolment in the two groups. There was, however, a higher proportion of stunted infants in the biomass fuel exposed group. Adjusting for these growth variables did not alter the association between biomass fuel use and cognitive abilities, however, indicating that they are unlikely part of the causal pathway.

Strengths of the study include the large and well described cohort of children from a community-based study in an area where biomass fuel still is used for cooking and with follow up assessments of neurodevelopment. The cognitive measurements are collected in a highly qualified system of cognitive assessments; however, the tools are developed in the US, and are not formally validated for a Nepalese study setting. Cooking fuel type, measured by self-report during the enrollment procedures when the children were 6–11 months, was used as a proxy for HAP. Although not validated for this study, the question was validated in a previous study on HAP and ALRI at the study site (Bates et al., 2013, 2018). The self-report question has its limitations, however, in terms of quantification and timing of the exposure as well as a lack of information on the specific pollutants. Moreover, we have no information on secondary fuel used for cooking or fuels used for heating. Altogether these limitations in the exposure measurement could lead to exposure misclassification and push the associations towards the null. In other words, for the current study, more precise exposure measurements could have led to even stronger observed associations. Although the study includes multiple comparisons that could increase the risk of false positive results, it is important to acknowledge that the study had a clearly stated primary outcome defined a priori, and that secondary outcomes and subgroup analyses, also defined a priori, were included to further explore the association between HAP and different cognitive outcomes and in particular vulnerable subgroups. In other words, the purpose of these exploratory analyses was to improve our understanding of findings related to the primary objective. Another limitation to the current analyses is that some of the subgroups are small and thus there is a restricted statistical power to detect associations. On the one hand, restricting the participants to those who were mildly stunted could limit the external validity of our results. On the other hand, this led to a more homogenous population which again could have improved the internal validity through more precise effect estimates and lower risk of confounding by variables related to stunting.

To conclude, children living in households using biomass fuel for cooking had lower scores on overall cognitive abilities compared to children in homes with no biomass fuel use. Uncertainties of findings include exposure misclassification and unmeasured confounding. The association between HAP and neurodevelopment in children should be further explored in future studies with more precise measures of the exposure and including specific measurements of mechanisms in the developing brain. Despite the described uncertainties, we believe that the current findings in conjunction with the other well-described health consequences of HAP provide support for the global effort to reduce biomass fuel use.

Authors contribution

IK conceptualized and designed the study, supervised the data collection, and performed the statistical analyses, interpretation of results and drafting of the initial manuscript. **TAS** conceptualized and designed the study, coordinated, and supervised the data collection, performed the statistical analyses, interpretation of the results, reviewed and revised the manuscript, approved the final manuscript as submitted. **RKC** conceptualized and designed the study, coordinated, and supervised the data collection, reviewed and revised the manuscript, and approved the final manuscript as submitted. **CS** conceptualized and designed the study, supervised the data collection, and performed the statistical analyses, interpretation of results, reviewed and revised the manuscript and approved the final manuscript as submitted. **MU** coordinated, and supervised the data collection, reviewed and revised the manuscript, and approved the final manuscript as submitted. **SR** coordinated and supervised the data collection, reviewed and revised the manuscript, and approved the final manuscript as submitted. **MH** supervised the data collection, reviewed and revised the manuscript, and approved the final manuscript as submitted. **MS** supervised the data collection, reviewed and revised the manuscript, and approved the final manuscript as submitted. **LS** coordinated the data collection, reviewed and revised the manuscript, and approved the final manuscript as submitted.

Funding

This work was supported by the Thrasher Research Fund (award # 11,512), the GC Rieber foundation, the University of Bergen (UiB), and the Research Council of Norway through a grant to Centre for Intervention Science in Maternal and Child Health (CISMAC).

Ethical considerations

The study received ethical clearance from the Nepal Health Research Council (NHRC, #233/2014, #73/2017) and from the Regional Committee for Medical and Health Research Ethics (REC # 2014/1528) in Norway. We obtained written informed consent from caregivers after providing thorough information on the study procedures both for the main trial and for the follow-up.

Data sharing statement

Data available on request. To meet ethical requirements for the use of confidential patient data, requests must be approved by the Nepal Health Research Council (NHRC) and the Regional Committee for Medical and Health Research Ethics in Norway. Requests for data should be sent to the authors, by contacting Child Health Research Project, Department of Child Health, Institute of Medicine, Tribhuvan University (chrp2015@gmail.com), or by contacting the Department of Global Health and Primary Care at the University of Bergen (post@igs.uib.no).

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.

Acknowledgement

This work was supported by Thrasher Research Fund (award # 11512), the GC Rieber foundation, the University of Bergen (UiB), and the Research Council of Norway through a grant to Centre for Intervention Science in Maternal and Child Health (CISMAC). We thank the staff at the Child Health Research Project including the cognitive team, supervisors, data management team and all field workers. We are grateful to all participant children and their families for their valuable time to participate in the study. We are also grateful to Shyam Sunder Dhaubhadel and all staff at Siddhi Memorial Hospital.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2022.113265.

References

Ahammed, B., Maniruzzaman, M., Ferdausi, F., Abedin, M.M., Hossain, M.T., 2020. Socioeconomic and demographic factors associated with low birth weight in Nepal: data from 2016 Nepal demographic and health survey. Social Health and Behavior 3 (4), 158.

Allen, J., Klocke, C., Morris-Schaffer, K., Conrad, K., Sobolewski, M., Cory-Slechta, D., 2017. Cognitive effects of air pollution exposures and potential mechanistic underpinnings. Current environmental health reports 4 (2), 180–191.

Babadjouni, R.M., Hodis, D.M., Radwanski, R., Durazo, R., Patel, A., Liu, Q., et al., 2017. Clinical effects of air pollution on the central nervous system; a review. J. Clin. Neurosci. 43, 16–24.

Bansal, E., Hsu, H.-H., de Water, E., Martínez-Medina, S., Schnaas, L., Just, A.C., et al., 2021. Prenatal PM2. 5 exposure in the second and third trimesters predicts neurocognitive performance at age 9–10 years: a cohort study of Mexico City children. Environ. Res. 202, 111651.

Bartington, S.E., Bakolis, I., Devakumar, D., Kurmi, O.P., Gulliver, J., Chaube, G., et al., 2017. Patterns of domestic exposure to carbon monoxide and particulate matter in households using biomass fuel in Janakpur, Nepal. Environ. Pollut. 220 (Pt A), 38–45.

Bates, M.N., Chandyo, R.K., Valentiner-Branth, P., Pokhrel, A.K., Mathisen, M., Basnet, S., et al., 2013. Acute lower respiratory infection in childhood and household fuel use in Bhaktapur, Nepal. Environ. Health Perspect. 121 (5), 637–642.

Bates, M.N., Pokhrel, A.K., Chandyo, R.K., Valentiner-Branth, P., Mathisen, M., Basnet, S., et al., 2018. Kitchen PM2. 5 concentrations and child acute lower respiratory infection in Bhaktapur, Nepal: the importance of fuel type. Environ. Res. 161, 546–553.

Bellinger, D.C., 2018. Environmental chemical exposures and neurodevelopmental impairments in children. Pediatric Medicine 1.

Brabhukumr, A., Malhi, P., Ravindra, K., Lakshmi, P., 2020. Exposure to household air pollution during first 3 years of life and IQ level among 6–8-year-old children in India–A cross-sectional study. Sci. Total Environ. 709, 135110.

Brooks, B.L., Sherman, E.M., Strauss, E., 2009. NEPSY-II: a developmental neuropsychological assessment. Child Neuropsychol. 16 (1), 80–101.

Bruce, N., Perez-Padilla, R., Albalak, R., 2000. Indoor air pollution in developing countries: a major environmental and public health challenge. Bull. World Health Organ. 78, 1078–1092.

Burning, W.H.O., 2016. Opportunity: Clean Household Energy for Health, Sustainable Development, and Wellbeing of Women and Children. Report No.: 9241565233.

Central Bureau of Statistics, 2021. National Population and Housing Census. Preliminary Report. Central Bureau of Statistics.

Clifford, A., Lang, L., Chen, R., Anstey, K.J., Seaton, A., 2016. Exposure to air pollution and cognitive functioning across the life course–a systematic literature review. Environ. Res. 147, 383–398.

CLIMATE-DATA.org, 2022. https://en.climate-data.org/asia/nepal-26/. accessed March, 2022.

Costa, L.G., Cole, T.B., Dao, K., Chang, Y.-C., Coburn, J., Garrick, J.M., 2020. Effects of air pollution on the nervous system and its possible role in neurodevelopmental and neurodegenerative disorders. Pharmacol. Ther. 210, 107523.

Devakumar, D., Semple, S., Osrin, D., Yadav, S.K., Kurmi, O.P., Saville, N.M., et al., 2014. Biomass fuel use and the exposure of children to particulate air pollution in southern Nepal. Environ. Int. 66, 79–87.

Dix-Cooper, L., Eskenazi, B., Romero, C., Balmes, J., Smith, K.R., 2012. Neurodevelopmental performance among school age children in rural Guatemala is associated with prenatal and postnatal exposure to carbon monoxide, a marker for exposure to woodsmoke. Neurotoxicology 33 (2), 246–254.

Fox, S.E., Levitt, P., Nelson 3rd, C.A., 2010. How the timing and quality of early experiences influence the development of brain architecture. Child Dev. 81 (1), 28–40.

Fullerton, D.G., Bruce, N., Gordon, S.B., 2008. Indoor air pollution from biomass fuel smoke is a major health concern in the developing world. Trans. Roy. Soc. Trop. Med. Hyg. 102 (9), 843–851.

IEA, 2017. Energy access outlook 2017. International Energy Agency, Paris.

Institute for Health Metrics and Evaluation. Nepal. https://www.healthdata.org/nepal. Accessed March 2022.

Julvez, J., López-Vicente, M., Warembourg, C., Maitre, L., Philippat, C., Gützkow, K.B., et al., 2021. Early life multiple exposures and child cognitive function: a multi-centric birth cohort study in six European countries. Environ. Pollut. 117404.

Kc, R.K., Nakarmi, A.M., 2021. Urban energy scenario of household sector in Bhaktapur municipality for sustainable energy development. Journal of Advanced College of Engineering and Management 6, 99–109.

Korkman, M., Kirk, U., Kemp, S., NEPSY, 1998. A Developmental Neuropsychological Assessment Manual. The Psychological Corporation, San Antonio, TX.

Kyu, H.H., Georgiades, K., Boyle, M.H., 2009. Maternal smoking, biofuel smoke exposure and child height-for-age in seven developing countries. Int. J. Epidemiol. 38 (5), 1342–1350.

Mannucci, P.M., Franchini, M., 2017. Health effects of ambient air pollution in developing countries. Int. J. Environ. Res. Publ. Health 14 (9), 1048.

McCoy, D.C., Peet, E.D., Ezzati, M., Danaei, G., Black, M.M., Sudfeld, C.R., et al., 2016. Early childhood developmental status in low- and middle-income countries: national, regional, and global prevalence estimates using predictive modeling. PLoS Med. 13 (6), e1002034.

Ministry of Health, Nepal, 2017. Nepal Demographic and Health Survey 2016. Ministry of Health Nepal, Kathmandu.

Murray, C.J., Aravkin, A.Y., Zheng, P., Abbafati, C., Abbas, K.M., Abbasi-Kangevari, M., et al., 2020. Global burden of 87 risk factors in 204 countries and territories, 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019. Lancet 396 (10258), 1223–1249.

Nazif-Muñoz, J.I., Spengler, J.D., Arku, R.E., Oulhote, Y., 2020. Solid fuel use and early child development disparities in Ghana: analyses by gender and urbanicity. J. Expo. Sci. Environ. Epidemiol. 30 (4), 698–706.

Pokhrel, A.K., Bates, M.N., Acharya, J., Valentiner-Branth, P., Chandyo, R.K., Shrestha, P. S., et al., 2015. PM2. 5 in household kitchens of Bhaktapur, Nepal, using four different cooking fuels. Atmos. Environ. 113, 159–168.

Psaki, S.R., Seidman, J.C., Miller, M., Gottlieb, M., Bhutta, Z.A., Ahmed, T., et al., 2014. Measuring socioeconomic status in multicountry studies: results from the eight-country MAL-ED study. Popul. Health Metrics 12 (1), 1–11.

Sania, A., Sudfeld, C.R., Danaei, G., Fink, G., McCoy, D.C., Zhu, Z., et al., 2019. Early life risk factors of motor, cognitive and language development: a pooled analysis of studies from low/middle-income countries. BMJ Open 9 (10), e026449.

Shrestha, P.S., Shrestha, S.K., Bodhidatta, L., Strand, T., Shrestha, B., Shrestha, R., et al., 2014. Bhaktapur, Nepal: the MAL-ED birth cohort study in Nepal. Clin. Infect. Dis. 59 (Suppl. 4), S300–S303.

Smith, K.R., Bruce, N., Balakrishnan, K., Adair-Rohani, H., Balmes, J., Chafe, Z., et al., 2014. Millions dead: how do we know and what does it mean? Methods used in the comparative risk assessment of household air pollution. Annu. Rev. Publ. Health 35, 185–206.

Strand, T.A., Ulak, M., Chandyo, R.K., Kvestad, I., Hysing, M., Shrestha, M., et al., 2017. The effect of vitamin B12 supplementation in Nepalese infants on growth and development: study protocol for a randomized controlled trial. Trials 18 (1), 187.

Strand, T.A., Ulak, M., Hysing, M., Ranjitkar, S., Kvestad, I., Shrestha, M., et al., 2020. Effects of vitamin B12 supplementation on neurodevelopment and growth in Nepalese Infants: a randomized controlled trial. PLoS Med. 17 (12), e1003430.

Suades-González, E., Gascon, M., Guxens, M., Sunyer, J., 2015. Air pollution and neuropsychological development: a review of the latest evidence. Endocrinology 156 (10), 3473–3482.

Sudfeld, C.R., Charles McCoy, D., Danaei, G., Fink, G., Ezzati, M., Andrews, K.G., et al., 2015. Linear growth and child development in low- and middle-income countries: a meta-analysis. Pediatrics 135 (5), e1266–e1275.

Ulak, M., Chandyo, R.K., Thorne-Lyman, A.L., Henjum, S., Ueland, P.M., Midttun, O., et al., 2016. Vitamin status among breastfed infants in Bhaktapur, Nepal. Nutrients 8 (3).

Ulak, M, Kvestad, I, Chandyo, R, Ranjitkar, S, Hysing, M, Schwinger, C, et al., 2022. The effect of infant vitamin B12 supplementation on neurodevelopment: a follow-up of a randomized placebo-controlled trial in Nepal. Br. J. Nutr. 1–18.

Wechsler, D., 2012. Wechsler Preschool and Primary Scale of Intelligence, fourth ed. Pearson Assessment, London.

WHO, 2006. WHO Child Growth Standards: Methods and Development: Length/height-For-Age, Weight-For-Age, Weight-For-Length, Weight-For-Height and Body Mass Index-For-Age. World Health Organization Multicentre Growth Reference Study, Geneva.

WHO, 2014. WHO Indoor Air Quality Guidelines: Household Fuel Combustion. World Health Organization, Geneva.