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Socioeconomic inequalities and ambient air pollution exposure in school-aged children living in an affluent society: an analysis on individual and aggregated data in Belgium

Tehreem Mustansar [a,*], Erik J. Timmermans [a], Ana Inês Silva [b], Esmée M. Bijnens [b,c], Wouter Lefebvre [d], Nelly D. Saenen [b], Charlotte Vanpoucke [e], Tim S. Nawrot [b], Ilonca Vaartjes [a]

[a] Julius Center for Health Sciences and Primary Care, University Medical Center Utrecht, Utrecht University, Utrecht, the Netherlands
[b] Centre for Environmental Sciences, Hasselt University, Diepenbeek, Belgium
[c] Department of Environmental Sciences, Faculty of Science, Open University, the Netherlands
[d] Flemish Institute for Technological Research (VITO), Mol, Belgium
[e] Belgian Interregional Environment Agency (IRCELINE), Brussels, Belgium

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ABSTRACT

Background: Individuals with lower socioeconomic status (SES) are at a higher risk of being exposed to adverse environmental factors. Children are more vulnerable to the harmful effects of air pollutants. Therefore, this study examined socioeconomic inequalities in air pollution exposure among children in Flanders, Belgium.

Methods: Data were used from 298 children (age range: 9–12 years), and from their parents who participated in the COGNition and Air pollution in Children study. Socioeconomic status was measured using highest parental education at the individual level and median income at the neighborhood (aggregated) level. Annual average outdoor concentrations of particulate matter with diameters <2.5 μm ($PM_{2.5}$) and <10.0 μm (PM_{10}), nitrogen dioxide (NO_2), and black carbon (BC) in μg/m^3 were estimated at the residential address. Mixed regression models were applied to examine the associations.

Results: Children from parents with a low education level were exposed to significantly higher levels of $PM_{2.5}$, PM_{10}, and BC compared to children from parents with a high education level. However, the associations were not significant when tested using regression models. Children who lived in areas with a lower median neighborhood income were exposed to significantly higher levels of air pollution; an interquartile range (IQR; €4505.00) decrease in income was associated with an increase in exposure to $PM_{2.5}$ of 0.198 μg/m^3, PM_{10} of 0.406 μg/m^3, NO_2 of 0.740 μg/m^3, and BC of 0.063 μg/m^3. Children of parents with a low/high education level had a higher exposure to $PM_{2.5}$, PM_{10}, NO_2, and BC when living in a low income neighborhood. Exposure to all air pollutants was the highest for low parental education level and low neighborhood income. **Conclusions**: Low neighborhood income was significantly associated with higher levels of air pollution, while parental education level was not significantly associated. Children from parents with a low education and low income were exposed to the highest levels of air pollution.

1. Background

The adverse health effects of exposure to air pollution are well-established (Bu et al., 2021; de Bont et al., 2022; Liu et al., 2023; Clifford et al., 2016; de Zwart et al., 2018). There were, in total, 368,000 estimated deaths in Europe in 2019 attributable to air pollution (Juginović et al., 2021). Children are suggested to be more vulnerable to the harmful effects of air pollutants, because their defense mechanisms are still evolving, and they inhale a higher volume of air pollutants per body weight than adults (Salvi, 2007). Higher levels of particulate air pollution in early life have been shown to decrease lung function (Gehring et al., 2013) and unfavorable change the arterial wall (Ntarladima et al., 2019) during childhood. Furthermore, there is evidence for decreased cognitive function (Sunyer, 2008; Saenen et al.,

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* Corresponding author.
E-mail address: t.mustansar@umcutrecht.nl (T. Mustansar).

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2016), increased cardiovascular morbidity and mortality (Nawrot et al., 2011; Brook et al., 2010) and respiratory diseases (Guerra et al., 2015) and lung cancer (Raaschou-Nielsen et al., 2013) later in life (Kim et al., 2018).

In particular, children from parents with a low socioeconomic status (SES) are more likely to be exposed to adverse environmental factors in their living environment, including higher levels of air pollution (Mathiarasan and Hüls, 2021; Chaix et al., 2006). Education and income are both indicators of SES. However, these are separate constructs that may show independent associations with health outcomes. While income is an indication of material resources, education has been shown to be a better predictor of psychosocial resources such as the ability to manage social systems (e.g. the healthcare system), increase social support, regulate personal health behaviors, and achieve personal control (Cutler et al.). Higher education is often expected to result in higher wages (Kromydas, 2017; Veselinović et al., 2020; Cheah et al.). However, in practice, it is more complicated and as such some higher educated individuals can reside in low income neighborhoods (Kromydas, 2017; Veselinović et al., 2020; Cheah et al.). The geospatial distribution for income and education might, therefore, somewhat differ, and consequently exposure to air pollution as well.

The majority of previous studies viewed inequalities in air pollution exposure by income and education separately (Chaix et al., 2006; Hajat et al., 2015; Bolte et al., 2005). However, there might be a joint effect as well, meaning that children who live in low income neighborhoods and who have parents with a low education level might be exposed to even higher levels of air pollution. Therefore, the present study aims to investigate differences in air pollution exposure among school-aged children by neighborhood income, parental education level, and the combined effect of neighborhood income and parental education level. It is hypothesized that children who live in low income neighborhoods or who have parents with a low education level are exposed to higher levels of air pollution, including particulate matter with diameters <2.5 μm ($PM_{2.5}$) and <10.0 μm (PM_{10}), nitrogen dioxide (NO_2), and black carbon (BC). Furthermore, it is hypothesized that children with low educated parents who also live in low income neighborhoods are exposed to substantially higher air pollution levels compared to when only one indicator of low SES is present.

2. Methods

2.1. Study population

In this study, data from the COGNition and Air pollution in Children (COGNAC) study were used. In COGNAC, children aged 9–12 years were enrolled from three different primary schools in three different areas (Tienen, Zonhoven, and Hasselt) in Flanders, Belgium. In total, 770 children were invited to participate in the COGNAC study, of which 334 children (43.4 %) participated in the study between January 2012 and February 2014. Parents were asked to complete a questionnaire to obtain information about the parental education level, passive exposure to tobacco smoke, and child's ethnicity, residence, transportation and physical activity. The schools were situated in urban areas with a high traffic density. A more in depth description of the study population is provided by Saenen and colleagues (Saenen et al., 2016). Of all 334 children, 36 were excluded because of missing data in any of the variables included. Therefore, the sample included 298 children. The study protocol of the COGNAC study was approved by the Ethical Review Boards of Hasselt University and East-Limburg Hospital. Written informed consent was obtained from the parents and oral consent was obtained from the children.

2.2. Air pollution

Using a spatial-temporal interpolation method, the air pollution interpolation model (RIO), combined with a Gaussian dispersion model, the Immission Frequency Distribution Model, the daily average outdoor concentrations of $PM_{2.5}$, PM_{10}, NO_2, and BC in μg/m^3 have been estimated at the participants' addresses for the year before data collection (Lefebvre et al., 2013a; RIO-IFDM - English; Janssen et al., 2008). The interpolation method takes into account air pollution data of fixed monitoring stations (Lefebvre et al., 2013a; RIO-IFDM - English) in combination with land cover data derived from satellite images in the CORINE land-cover dataset (Janssen et al., 2008). Daily interpolated exposure concentrations for $PM_{2.5}$, PM_{10}, NO_2 and BC were calculated by the model in a high-resolution receptor grid taking into account information from the Belgian telemetric air quality networks, large industrial point emission sources, and line emission sources from road transport. Model performance was evaluated through leave-one-out cross-validation and was based on 34 monitoring points for $PM_{2.5}$, 58 monitoring points for PM_{10}, 67 stations for NO_2, and 14 monitoring points for BC. A spatial temporal model explained variance of 0.80 for $PM_{2.5}$, (Janssen et al., 2008), 0.70 for PM_{10}, (Janssen et al., 2008), 0.78 for NO_2 (Maiheu et al., 2013), 0.74 for BC (Lefebvre et al., 2011) was obtained from the interpolation tool. Furthermore, RMSE (spatial) value was 1.83 μg/m^3 for $PM_{2.5}$(IRCELINE, 2016), 4.39 μg/m^3 for PM_{10} (Lefebvre et al., 2013b) and 7.56 μg/m^3 for NO_2 (Lefebvre et al., 2013b). For BC, the RMSE value was 0.32 μg/m^3 (Lefebvre et al., 2011). In addition, NO_2 was validated with a passive sampler campaign (17886 measurements) and an RMSE of 5.2 μg/m^3 was found (Hooyberghs et al., 2022). These validation statistics indicate appropriate model performance. The model was further validated by a study that showed that urinary BC load was associated with annual residential modeled concentration (Saenen et al., 2017) and with placental BC load (Bongaerts et al., 2022). This suggests that, despite potential variations in personal exposure, the modeled pollution levels at the residential address still capture meaningful long-term exposure trends that influence biological responses. Therefore, this association supports the use of the model for epidemiological studies, as it demonstrates a measurable link between estimated pollution levels and internal health markers.

2.3. Indicators of socioeconomic status (SES)

In the present study, two indicators of SES were used, including parental education level and median neighborhood income. Parental education level was measured as the highest attained education level by the father and mother via questionnaires (e.g., if the mother had general secondary education and the father had no diploma then secondary education was assigned as the parental education). Parental education level was dichotomized into low (reference category; i.e., no diploma, primary education, vocational secondary education, secondary technical education, and general secondary education) and high (i.e., academy and university). Continuous data on median neighborhood income in Euros for administrative statistical sectors in 2012 were obtained from the Statistical Office Belgium, (Fiscal statistics on income by Statistical sector) and linked to participants using their residential addresses. Administrative statistical sectors are the smallest administrative areas in Belgium. The average size of these areas is 1.54 km^2 and these areas include, on average, 537 residents (Statistical sectors 2011–2017, 2017).

In order to obtain a variable that encompasses both neighborhood income and parental education level, we first dichotomized the continuous measure of neighborhood income, based on the mean neighborhood income of the study sample, into low neighborhood income (<€25,443.58) and high neighborhood income (≥€25,443.58). Subsequently, we combined this dichotomized variable with the dichotomized measure of parental education level to create four mutually exclusive categories: (1) low education and low income (reference category), (2) low education and high income, (3) high education and low income, and (4) high education and high income.

2.4. Covariates

The analyses were adjusted for age in years and sex (boy versus girl). Additionally, the association of neighborhood income with air pollution exposure was adjusted for the dichotomized parental education level.

2.5. Statistical analysis

Characteristics of the study population and the area-level measures are presented using descriptive statistics for the full population as well as for each SES group, separately. Independent sample T-tests and One-way Analysis of Variance (ANOVA) were conducted to compare groups when appropriate. If One-way ANOVA indicated significant differences across groups, Tukey's Honestly Significant Difference post-hoc tests were conducted to examine which specific groups differed significantly from each other. Mixed regression models were applied to examine associations of parental education level and neighborhood income (as a continuous variable) with the various air pollution exposure measures. The associations were adjusted for age and sex. The associations of neighborhood income with air pollution exposures were additionally adjusted for parental education level. A step-wise approach was followed to understand the individual and combined effects of these covariates on the exposure. In order to adjust for clustering, school (i.e., Tienen, Zonhoven, and Hasselt) was included as a random factor in all mixed regression models. The associations of neighborhood income with air pollution exposures are presented as one interquartile range (IQR) increase in income by multiplying the coefficients with the IQR of neighborhood income. In all statistical analyses, a p-value below 0.05 was considered statistically significant. All analyses were performed in R version 4.1.3.

3. Results

3.1. Descriptive characteristics

Characteristics of the study population and all relevant area-level exposure measures are presented in Table 1. From all included 298 children, 149 (50.0 %) were girls, and the mean age was 10.2 ± 1.2 years. In the study sample, there were 81 (27.2 %) children with low parental education level and 217 (72.8 %) children with a high parental education level. The average median neighborhood income was €25,444.00 (SD = €2910.50). In the full study population, the average exposure levels to $PM_{2.5}$, PM_{10}, NO_2, and BC were 15.0 μg/m^3 (SD = 0.8 μg/m^3), 20.4 μg/m^3 (SD = 1.6 μg/m^3), 20.9 μg/m^3 (SD = 1.9 μg/m^3), and 1.5 μg/m^3 (SD = 0.2 μg/m^3), respectively.

As shown in Table 1, children from parents with a low education level were exposed to significantly higher levels of $PM_{2.5}$, $PM_{10,}$ and BC compared to children from parents with a high education level. Children living in low income neighborhoods were exposed to significantly higher levels of $PM_{2.5}$, PM_{10}, $NO_{2,}$ and BC compared to children living in high income neighborhoods.

3.2. Associations of parental education level with air pollution exposures

Table 2 presents the associations of parental education level with air pollution exposures in the study sample. The positive associations in all models indicated that children from parents with a low education level were exposed to higher air pollution levels than those from parents with a high education level, although none of these associations were statistically significant. The fully adjusted models indicate the following associations of parental education level with air pollution exposure (Table 2, Model 2): $\beta_{PM2.5} =$ 0.037, 95 % CI = −0.117,0.194; $\beta_{PM10} =$ 0.192, 95 % CI = −0.129,0.516; $\beta_{NO2} =$ 0.394, 95 % CI = −0.129,0.916, $\beta_{BC} =$ 0.023, 95 % CI = −0.016,0.063). This suggests that children from parents with a low education are exposed to increased levels of $PM_{2.5}$ by 0.037 μg/m^3, PM_{10} by 0.192 μg/m^3, NO_2 by 0.394 μg/m^3, and BC by 0.023 μg/m^3 compared to those from parents with higher education. Upon adjusting for age and sex in Model 2, the strength of the associations slightly changed, yet remained non-significant. This suggests that these demographic factors did not markedly influence the observed associations.

3.3. Associations of neighborhood income with air pollution exposures

Table 2 also presents the associations of neighborhood income with air pollution exposures in the study population. The negative associations in all models consistently indicated that children living in areas that are characterized by a higher neighborhood income are exposed to significantly lower levels of air pollution. The fully adjusted models (Model 3) indicate the following associations of neighborhood income

Table 1
Individual-level and area-level characteristics in the full sample, stratified by parental education level and neighborhood income. [a,b]

Variables	Full study population	Parental education level		Neighborhood income	
	All (n=298)	**Low (n=81)**	**High (n=217)**	**Low (n=166)**	**High (n=132)**
Individual-level characteristics					
Age (in years) [Mean ± SD]	10.2 ± 1.2	10.8 ± 1.3	10.1 ± 1.2	10.2 ± 1.3	10.2 ± 1.3
Sex (n (%))	149 (50.0)	44 (54.3)	105 (48.4)	78 (47.0)	71 (53.8)
Male	149 (50.0)	37 (45.7)	112 (51.6)	88 (53.0)	61 (46.2)
Female					
Education level (n (%))	81 (27.2)	81 (100.0)	0 (0.0)	52 (31.3)	29 (22.0)
Low	217 (82.8)	0 (0.0)	217 (100.0)	114 (68.7)	103 (78.0)
High					
School (n (%))	72 (24.2)	13 (16.0)	59 (27.3)	13 (7.8)	59 (44.7)
Kiewit	59 (19.8)	24 (29.7)	35 (16.1)	34 (20.5)	25 (18.9)
Tienen	167 (56.0)	44 (54.3)	123 (56.6)	119 (71.7)	48 (36.3)
Zonhoven					
Area-level characteristics					
Neighborhood income (in Euros) [Mean ± SD]	25,444 ± 2910	24,873 ± 2409	25,657 ± 3054.5	23,301 ± 1460	27,831 ± 1838.9
Annual average outdoor concentration of $PM_{2.5}$ (in μg/m^3) [Mean ± SD]	15.0 ± 0.8	**15.2 ± 0.8**	**15.0 ± 0.8**	**15.2 ± 0.8**	**14.9 ± 0.8**
Annual average outdoor concentration of PM_{10} (in μg/m^3) [Mean ± SD]	20.4 ± 1.6	**20.8 ± 1.6**	**20.3 ± 1.5**	**20.6 ± 1.5**	**20.1 ± 1 0.6**
Annual average outdoor concentration of NO_2 (in μg/m^3) [Mean ± SD]	20.9 ± 1.9	21.2 ± 2.0	20.8 ± 1.9	**21.3 ± 1.6**	**20.5 ± 2.1**
Annual average outdoor concentration of BC (in μg/m^3) [Mean ± SD]	1.5 ± 0.2	**1.6 ± 0.2**	**1.5 ± 0.2**	**1.6 ± 0.1**	**1.4 ± 0.2**

[a] Abbreviations: BC = black carbon; kg = kilogram; m = meter; n = number; NO_2 = nitrogen dioxide; $PM_{2.5}$ = particulate matter with diameter <2.5 μm; PM_{10} = particulate matter with diameter <10.0 μm; SD = standard deviation.

[b] The descriptive statistics of the characteristics that are presented in bold significantly differ between the groups (i.e., p-value<0.05, derived from ANOVA).

Table 2
Associations of parental education level and neighborhood income with air pollution exposure in children.[a-d]

Exposure variables	Model 1: β (95 % CI)	Model 2: β (95 % CI)	Model 3: β (95 % CI)
	Associations of parental education level (categorical measure) with air pollution exposure		
PM2.5	0.068 (−0.083, 0.221)	0.015 (−0.133, 0.165)	–
PM10	0.136 (−0.168, 0.444)	0.147 (−0.161, 0.458)	–
NO2	0.384 (−0.108, 0.877)	0.389 (−0.111, 0.890)	–
BC	0.026 (−0.011, 0.064)	0.021 (−0.017, 0.060)	–
	Associations of median neighborhood income (continuous measure) with air pollution exposure		
	Model 1: β (95 % CI)	Model 2: β (95 % CI)	Model 3: β (95 % CI)
PM2.5	−0.168 (−0.280, −0.056)	−0.196 (−0.306, −0.088)	−0.198 (−0.307, −0.089)
PM10	−0.414 (−0.639, −0.191)	−0.414 (−0.640, −0.189)	−0.406 (−0.634, −0.181)
NO2	−0.749 (−1.090, −0.324)	−0.763 (−1.106, −0.332)	−0.740 (−1.085, −0.304)
BC	−0.060 (−0.089, −0.034)	−0.064 (−0.093, −0.037)	−0.063 (−0.092, −0.036)

[a] Abbreviations: BC = black carbon; CI = confidence interval; $PM_{2.5}$ = particulate matter with diameter ≤2.5 μm; PM_{10} = particulate matter with diameter ≤10.0 μm; NO_2 = nitrogen dioxide.
[b] The associations in Model 1 are unadjusted. The associations in Model 2 are adjusted for age and sex. The associations in Model 3 are additionally adjusted for parental education. In all models, school was included as a random factor.
[c] The reference category for parental education is high parental education level.
[d] The associations presented in bold are statistically significant (i.e., p-value<0.05).

with air pollution exposure for each IQR increase (€4505.00) in income: ($\beta_{PM2.5} = -0.198$, 95 % CI = −0.307, −0.089; $\beta_{PM10} = -0.406$, 95 % CI = −0.634, −0.181; $\beta_{NO2} = -0.740$, 95 % CI = −1.085, −0.304, $\beta_{BC} =$ −0.063, 95 % CI = −0.092,-0.036). For each IQR increase in income, $PM_{2.5}$, PM_{10}, NO_2, and BC exposures decrease by 0.198 μg/m^3, 0.406 μg/m^3, 0.740 μg/m^3, 0.063 μg/m^3 respectively. After progressively adjusting for age, sex, and parental education level in Model 3, the strength of the associations slightly changed compared to Models 1 and 2. This suggests that these demographic factors did not markedly influence the observed associations.

3.4. *The joint effect of education and income on air pollution exposure*

As shown in Table 3, exposure to $PM_{2.5}$, PM_{10}, NO_2, and BC was the lowest for children from parents with a high education and high income. Within the group of children from parents with a low education level, exposure to all air pollutants was highest for children living in a low income neighborhood. The results of the post-hoc tests revealed that the exposure difference between these two groups was statistically significant for all four pollutants. Furthermore, similar results were observed within the group of children from parents with a high education level. Children living in a low income neighborhood were exposed to significantly higher levels of PM_{10}, NO_2, and BC than the ones living in high income neighborhoods.

As shown in Table 4, the findings of the regression analyses confirmed that children from parents with a high educational level and a high income were exposed to significantly lower levels of air pollution

Table 4
Joint associations of education and income with air pollution exposure.[a,b,c]

Exposure variables	Categories of joint effects: β (95 % CI)		
	Low Education and High Income	High Education and Low Income	High Education and High Income
$PM_{2.5}$	−0.187 (−0.449, 0.073)	0.040 (−0.146, 0.225)	**−0.230 (-0.430, -0.032)**
PM_{10}	−0.336 (−0.877, 0.202)	0.008 (−0.377, 0.390)	**−0.601 (-1.015, -0.192)**
NO_2	−0.935 (−1.780, 0.003)	−0.277 (−0.904, 0.342)	**−1.251 (-1.884, -0.510)**
BC	−0.085 (−0.152, −0.020)	−0.012 (−0.059, 0.034)	**−0.098 (-0.149, -0.049)**

[a] Abbreviations: BC = black carbon; $PM_{2.5}$ = particulate matter with diameter ≤2.5 μm; PM_{10} = particulate matter with diameter ≤10.0 μm; NO_2 = nitrogen dioxide.
[b] The reference category is Low Education and Low Income.
[c] The associations presented in bold are statistically significant (i.e., p-value<0.05).

Table 3
Air pollution exposure in education and the joint effect of education and income.[a,b,c]

	Low parental education level			High parental education level		
	Low education	Low education and low income area	Low education and high income area	High education	High education and low income area	High education and high income area
Air pollution (in μg/m^3) [Mean ± SD]						
Annual average outdoor concentration of $PM_{2.5}$	15.2 ± 0.8	15.3 ± 0.9	15.1 ± 0.8	**15.0 ± 0.8**	**15.1 ± 0.8**	**14.9 ± 0.8**
Annual average outdoor concentration of PM_{10}	20.8 ± 1.6	20.9 ± 1.5	20.5 ± 1.7	**20.3 ± 1.5**	**20.5 ± 1.5**	**20.0 ± 1.5**
Annual average outdoor concentration of NO_2	21.2 ± 2.0	21.5 ± 1.7	20.7 ± 2.3	**20.8 ± 1.9**	**21.2 ± 1.8**	**20.4 ± 2.0**
Annual average outdoor concentration of BC	**1.6 ± 0.2**	**1.6 ± 0.2**	**1.5 ± 0.2**	**1.5 ± 0.2**	**1.6 ± 0.1**	**1.4 ± 0.1**

[a] Abbreviations: BC = black carbon; $PM_{2.5}$ = particulate matter with diameter ≤2.5 μm; PM_{10} = particulate matter with diameter ≤10.0 μm; NO_2 = nitrogen dioxide; SD = standard deviation.
[b] The descriptive statistics of the characteristics that are presented in bold significantly differ between the groups (i.e., p-value<0.05, derived from ANOVA).
[c] Post-hoc tests revealed a significant difference between the groups with low education and low income with high education and high income for $PM_{2.5}$, PM_{10}, NO_2, and BC. In addition, there was a significant difference between the groups high education and low income with high education and high income for PM_{10}, NO_2, and BC. Furthermore, there was a significant difference between the groups low education and low income with low education and high income for BC.

($\beta_{PM2.5} = -0.230$, 95 % CI = −0.430, −0.032; $\beta_{PM10} = -0.601$, 95 % CI = −1.015, −0.192; $\beta_{NO2} = -1.25$, 95 % CI = −1.884, −0.510, $\beta_{BC} = -0.098$, 95 % CI = −0.149, −0.049) compared to those with parents with a low educational level and a low income.

4. Discussion

The primary objective of this study was to investigate socioeconomic inequalities in air pollution exposure among school-aged children in Flanders, Belgium. The results revealed that children living in areas with lower neighborhood income were consistently exposed to significantly higher levels of ambient air pollution. However, parental education level was not significantly associated with air pollution exposure. When looking at the joint effect of education and income, we observed that exposure to all air pollutants was the lowest for the most favorable combination (i.e., high education and high income). Children of parents with a low education level have a higher exposure to $PM_{2.5}$, PM_{10}, NO_2, and BC when living in a low income neighborhood compared to a high income neighborhood, although only statistically significant for BC exposure.

4.1. Strengths and limitations

This is the first study from Flanders, Belgium that informs about air quality disparities in children based on socioeconomic status, which combines individual-level parental education and neighborhood-level income. This study provides valuable insights into the associations of neighborhood income and parental education level with air pollution exposure among school-aged children, and this is the first study that also takes into account the joint effect of income and education on air pollution exposure in this group.

However, some limitations also need to be acknowledged. The study's cross-sectional design makes it not possible to establish causality, and the findings may be influenced by unmeasured confounding variables, such as green space and ethnicity (Hajat et al., 2015; Fecht et al., 2015). Furthermore, the small sample size and the relatively small study area may limit the generalizability of the present findings.

Socioeconomic status is often measured by (a combination of) various indicators, such as education, income, and occupational status. Due to data availability in the COGNAC study, the present study, however, only focused on parental education level and neighborhood income as indicators of SES.

In addition, the present study only focused on air pollution exposure at the residential address, while children also spend a significant amount of their time at other places. Although time-activity integrated exposure measures could appropriately take this into account, previous studies have shown that estimates based on residential location only and time-activity-based estimates are highly correlated and result in similar findings (Hoek et al., 2024; Ntarladima et al., 2021).

Furthermore, the spatial variability of $PM_{2.5}$ is lower than that of NO_2, as $PM_{2.5}$ is influenced not only by local sources but also by atmospheric chemistry and long-range transport (Eeftens et al., 2015; Song et al., 2018). This characteristic may limit the sensitivity of $PM_{2.5}$ in detecting small-scale SES disparities in exposure.

4.2. Potential explanations and comparison with previous studies

The initial hypothesis that children from parents with lower education levels or from low income neighborhoods would be exposed to higher levels of air pollution was only partially supported by the findings of this study. Additionally, the initial hypothesis that children from parents with both low education and low income would be exposed to higher levels of air pollution was fully supported by the findings of this study.

Higher exposure levels were observed for $PM_{2.5}$, PM_{10}, NO_2, and BC in children from low educated parents, and the differences were significant for $PM_{2.5}$, PM_{10}, and BC. However, the regression analyses did not reveal statistically significant associations between parental education level and any of the air pollution exposure measures.

In contrast, the present study indicated a consistent and statistically significant association between neighborhood income and air pollution exposure. Children living in areas characterized by higher median neighborhood income were exposed to significantly lower levels of $PM_{2.5}$, PM_{10}, NO_2, and BC. The statistical significance of these associations persisted across all models, highlighting a robust relationship between neighborhood income and air pollution exposure. These findings align with previous research indicating that neighborhoods with lower socioeconomic status tend to have poor air quality (Fecht et al., 2015; Hajat et al., 2013; Padilla et al., 2014; Pearce et al., 2010; Chakraborty and Zandbergen, 2007).

In the joint group analyses, it was observed that children with parents with both low education and low neighborhood income were exposed to the highest level of air pollutants. In addition, the results showed that the differences between groups were being driven by neighborhood income. The results indicated that children from parents with low education and low income were exposed to significantly higher levels of BC than children from parents with low education and high income, as well as high education and high income. Furthermore, the findings showed that children from parents with high education and low income were exposed to significantly higher levels of $PM_{2.5}$, PM_{10}, NO_2, and BC than those from parents with high education and high income. The regression analysis confirmed the hypothesis that children from parents with the most unfavorable combination of SES (low education and low income) were significantly more exposed than children from parents with the most favorable combination (high education and high income).

Parental education level may have an effect on air pollution exposure that is conditional on other variables or interacts with them, such as parental income and occupation. As noted earlier, low education level does not always translate into a lower income (Kromydas, 2017; Veselinović et al., 2020; Cheah et al.). As a result, some higher educated individuals with low income can reside in low income neighborhoods (Kromydas, 2017; Veselinović et al., 2020; Cheah et al.). It has also been observed in previous studies that individual level SES factors show a lower association with air pollution whereas area level SES has been shown to have higher association with air pollution exposure (Hajat et al., 2013).

4.3. Implications of the findings

Considering the well-established health risks associated with air pollution exposure in children (Salvi, 2007; Gehring et al., 2013; Ntarladima et al., 2019), addressing socioeconomic disparities in air pollution exposure is crucial for promoting health equity among children. By reducing disparities in exposure to harmful air pollutants, policymakers can contribute to creating healthier and more equitable living environments for all children, regardless of their socioeconomic background. The study's findings suggest that parental education level alone may not be a strong predictor of air pollution exposure among children. Instead, a combination of parental education and neighborhood income provides a more comprehensive understanding of socioeconomic disparities in air pollution exposure. Therefore, interventions should focus on groups with multiple unfavorable socioeconomic indicators, such as children from low educated parents residing in low income neighborhoods. By targeting these vulnerable populations, policymakers can work towards reducing the disproportionate burden of air pollution related health risks at local and regional levels.

4.4. Suggestions for future research

Future research could examine whether the observed socioeconomic inequalities in air pollution exposure contribute to health inequalities in children. This can be studied in larger and more diverse populations while considering additional socioeconomic and sociodemographic factors, such as parental income, occupation and ethnicity. The intersecting effects of multiple socioeconomic factors, such as parental education, income, ethnicity, and housing status, on air pollution exposure among children can be investigated as part of the intersectionality theory which posits that individuals experience overlapping systems of oppression and privilege based on their intersecting social identities (Heard et al., 2020). Thus, future research could adopt an intersectional approach to examine how various dimensions of social inequality interact to shape patterns of air pollution exposure and health disparities among children. Moreover, longitudinal studies would be beneficial in assessing the long term effects of differential air pollution exposure among children from various socioeconomic backgrounds. Finally, comparative studies across different regions could elucidate regional variations in the relationship between socioeconomic status and air pollution. Investigating regional variations in the relationship between SES and air pollution exposure can help researchers understand the generalizability of findings across diverse geographical contexts. Different regions may have unique socio-environmental dynamics, policy landscapes, and socioeconomic disparities that influence patterns of air pollution exposure (Hajat et al., 2015). Comparative studies can shed light on whether the observed associations between SES and air pollution exposure hold true across different regions or if they vary based on local contextual factors.

5. Conclusion

In conclusion, this study highlights the significant role of neighborhood income in shaping air pollution exposure disparities among school-aged children in Flanders, Belgium. Parental education level was not significantly associated with air pollution exposure. The distinct impact of neighborhood income, particularly in combination with low parental education level, highlights the vulnerability of children in economically disadvantaged areas to higher air pollution concentrations. Furthermore, as this study emphasizes, it is important to consider both individual and multiple or joint indicators to fully account for SES and air pollution inequalities. These findings call for targeted environmental justice efforts and policy interventions aimed at reducing air pollution exposure.

CRediT authorship contribution statement

Tehreem Mustansar: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Erik J. Timmermans:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization. **Ana Inês Silva:** Writing – review & editing, Conceptualization. **Esmée M. Bijnens:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Wouter Lefebvre:** Formal analysis. **Nelly D. Saenen:** Writing – review & editing, Investigation, Data curation. **Charlotte Vanpoucke:** Writing – review & editing, Formal analysis. **Tim S. Nawrot:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization. **Ilonca Vaartjes:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no competing interests.

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Data availability

The data that has been used is confidential.

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