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REVIEW

Air pollution and children's respiratory health: a scoping review of socioeconomic status as an effect modifier

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Abstract

Objectives Air pollution is a leading environmental risk, and socioeconomic status (SES) is postulated as an effect modifier, especially in children. There is a growing interest in exploring this modifier. The present manuscript reviews SES as an effect modifier in children's respiratory health.
Methods A search in the PubMed and SCOPUS databases was conducted in September 2017 to identify studies with the inclusion criteria of being centred on children, respiratory outcomes, air pollutants and SES measurement.
Results A total of 17 studies were included. Twelve used single SES variables, and the remaining studies included composite SES indices. Household income (9) and parental education (8) were frequently evaluated. The significance of the effect modifier was found in nine studies that demonstrated a higher risk for individuals living in a lower SES. Sources of heterogeneity included SES measurement, health outcomes and geographical aggregation.
Conclusions The results suggest a higher modification in the effect of SES, generally indicating greater risk for children in lower SES. Children's characteristics need to be more carefully theorized and measured in this area, including the use of transdisciplinary approaches.

Keywords Air pollution · Children's health · Respiratory diseases · Effect modifier · Socioeconomic status · Exposure assessment

Introduction

Air pollution is one of the leading environmental risks challenging human health. Around 300 million children live in urban areas, principally in low-income zones, where the air is considered toxic (UNICEF 2016). The stages in which children are physiologically vulnerable to physical, chemical and biological factors are known as windows of susceptibility (Selevan et al. 2000; Makri et al. 2004), which are related to the development of their respiratory, nervous, immunological and endocrine systems and have been subject to intensive investigations (Kessler 2014).

In the case of children's respiratory systems, the time of exposure during the windows of susceptibility could favour the development, exacerbation and prevalence of asthma (Clark et al. 2010; Samoli et al. 2011; Zeng et al. 2016), as well as an increase in hospital admissions due to respiratory infections, pneumonia, bronchitis (Ostro et al. 2009; Lothrop et al. 2017) and reduced lung development and

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function (Gauderman et al. 2002; Barraza-Villarreal et al. 2008; Hernández-Cadena et al. 2009).

Health disparities due to air pollution have been associated with socioeconomic status (SES) (Martenies et al. 2017; Thakur et al. 2013). Although SES attempts to capture an individuals' social position, welfare and potential to access certain goods and services (Campbell 1983), in this review, we include papers based on the variable name, regardless of the definition. Those disparities have documented material and social factors such as restricted access to healthcare services, limited access to higher education levels, unemployment and maternal conditions (Lee and Marmot 2005; Evans and Kantrowitz 2002; Evans 2006) as potential effect modifiers. Likewise, psychosocial stress, independent of or in synergy with SES, has a modifying effect on the health outcomes attributed to air pollution (Clougherty and Kubzansky 2009).

The link air pollution–SES is part of the environmental justice framework. Hornberg and Pauli (2007) refer to environmental justice as the "uneven distribution of environmental quality between different social groups", making specific mention of an inverse relationship between SES and exposure to environmental hazards. Regarding air pollution, this relationship has been linked to transportation infrastructures in poor neighbourhoods where people are more exposed to traffic-related air pollutants (TRAP) (Pratt et al. 2015) and in proximity to industrial zones (Holifield et al. 2009). In the case of children, there is more concern because they do not decide the conditions in which they live (Kessler 2014).

The studies mentioned above identified an increased vulnerability in low SES through different pathways. However, some studies reported that this effect could also be observed in high-SES groups or even a lack of effect modification of SES for respiratory health outcomes (Cakmak et al. 2006; Wilhelm et al. 2009). In this sense, it is relevant to understand the context under which the effect of SES is observed on children's health. In the coming decades, the prevalence of diseases such as bronchitis and asthma will significantly increase due to the increasing worldwide air pollution problem (OECD 2016), which could have a considerable impact on children living in conditions of poverty and deprivation (UNICEF 2016).

To broaden our knowledge about the context of and the gaps that contribute to the heterogeneity of those results, we conducted a review of the recent literature on the role of SES as an effect modifier in the relationship between air pollution and children's respiratory health.

Methods

We conducted a search of scientific papers published between January 2000 and December 2017 in environmental, public health, medical and social science journals. Since this period includes the years in which the United Nations, World Health Organization (WHO) and UNICEF promoted the development of children's environmental health indicators (WHO 2004), we expected to find a significant number of publications on this topic. PubMed and SCOPUS bibliographic databases were used. Only peer-reviewed papers in English were considered. Reviews and reports were excluded.

Search terms in the abstract, title and keywords that were related to the following terms ("air pollution") AND ("socioeconomic status" OR "socioeconomic" OR "vulnerability" OR "effect modifier" OR "neighbourhood" OR "deprivation" OR "poverty") AND ("children's health" OR "respiratory diseases" OR "health effects") were used to identify relevant publications. After applying it, we retained 203 papers that contained any of the terms. These studies were filtered according to the following inclusion criteria: respiratory effects, outdoor air pollution, role of SES and children; 57 articles were eligible.

Finally, an in-depth evaluation was conducted to identify the specific discussions of SES as an effect modifier, as stated by the authors in their results. Seventeen studies were finally chosen (Fig. 1). We extracted the following data to compare these studies: author, publication year, study area, age group of children, study design, methods to evaluate exposure and SES effect, SES measurement, health outcomes, limitations and key findings. We grouped the selected papers according to categories in terms of the

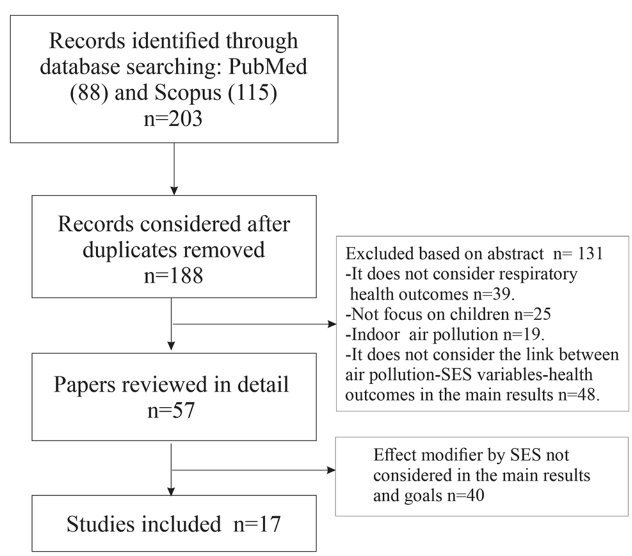


Fig. 1 Flow chart of the scoping review

SES measurement used (single-indicator variables or composite indices), the pollutant evaluated and health outcomes.

Results

Among the 17 selected articles, nine provided evidence of a statistically significant role of SES as an effect modifier (Lee et al. 2006; Lin et al. 2008; Burra et al. 2009; Delfino et al. 2009; Shankardass et al. 2009; Grineski et al. 2010; Alwahaibi et al. 2016; O'Lenick et al. 2017a, b) on the risk to suffer air pollution-related respiratory health outcomes. The overall evidence reflected a consistent pattern of an increased risk for children in low-SES groups, despite heterogeneity in the SES measurements used and the pollutants evaluated. The selected studies were conducted mainly in developed countries: the USA (10), Canada (3), South Korea (2), Oman (1) and Germany (1). We observed an increase in the number of studies in recent years: two between 2000 and 2006, eight between 2006 and 2012 and seven between 2012 and 2017.

SES measurements to assess the effect modification

SES is a complex concept, and in the reviewed papers, it was evaluated through either individual variables or composite indices. The impact of SES on the health of children has been evaluated by the following factors: structural (average household income, poverty level, insurance status, parental education level, unemployment, social cohesion) and material (material of walls, roof and floor of the dwelling, age of the house, infrastructure, material goods) (Lynch et al. 2000). Studies assessing psychosocial factors such as parental stress were included too.

We identified 12 articles that used a single-indicator variable as the SES measurement (Table 1), four studies that employed both single-indicator variables and a composite index for measurement and one study using only a composite index (Table 2).

The papers using composite indices usually include a mixture of variables focused on structural and material factors. Two used the Townsend index and two the neighbourhood deprivation index (NDI). In this group, we also included studies that used a set of variables from the psychosocial pathway (Shmool et al. 2014).

Among the 12 studies that used a single-indicator variable measurement of SES, six used an individual-level variable (through questionnaires applied to the parents) and six used a community-level variable (regional or postal code through census). Those studies conducted at the individual level reported more significant differences between strata than those studies performed at the community level.

Seven of the 12 studies that used single-measurement SES variables (Table 1) identified low SES as a potential effect modifier of respiratory health outcomes related to air pollution. Structural factors such as income (7), parental or maternal education (6) and health insurance (4) are frequently used. Household income was used as a proxy for other characteristics that influence living conditions; thus, the evaluation of this measure depicts different results. In studies at the community level (Lin et al. 2004; Burra et al. 2009), an association was found between mean income household, hospital admission for asthma and a large risk for children whose parental income is under the poverty line; however, effects in the opposite direction, i.e. a high risk for children in a high-SES strata (Delfino et al. 2009), were also reported. For the remaining studies that considered both income as a measure of SES at the individual level and different health outcomes (Hoffmann et al. 2009; Ebisu et al. 2011; Cakmak et al. 2016; Yi et al. 2017), there was a tendency towards a higher modifying effect on risk for low-SES strata. However, most associations were not significant, except for that of allergic rhinitis (Yi et al. 2017).

Concerning health insurance indicators and education level, we found a tendency to report substantial effect modifiers in the odds ratio (OR) of low-SES groups. For example, a birth cohort study (Lin et al. 2008) reported that children of mothers with a low education level and without health services guaranteed by Medicaid or self-payment present higher OR for asthma admission. This pattern was also noted by the examination of the new onset of asthma and respiratory symptoms assessed through parental education level (Shankardass et al. 2009; Ebisu et al. 2011; Cakmak et al. 2016).

Regarding composite indices, four studies used census data and one used variables directly obtained at the individual and family levels (Table 2). Two studies showed evidence of effect modification in the low SES (O'Lenick et al. 2017a, b). The studies using the Townsend index and NDI (Yap et al. 2013; O'Lenick et al. 2017b) for potential SES effect modification of respiratory health outcomes through counties/cities showed mixed results.

Among the studies, the inclusion of variables from the psychosocial pathway yielded mixed results. A higher modifying effect for low-SES strata was found in Shankardass et al. (2009) and Shmool et al. (2014), while Wilhelm et al. (2009) found it for high SES.

Additionally, the importance of stratifying the SES measurement was highlighted for both single-indicator variables and composite indices (O'Lenick et al. 2017a). When using a composite index, there was evidence of significant SES effect modification across strata. The

Table 1 Effect modifier evaluated through single-indicator variables of socioeconomic status (SES) in North America, Germany, South Korea and Oman from 2000 to 2017

Reference, location	Health outcomes	Age group	Air pollutant/exposure method	SES measurement	Level	Main results
Lin et al. (2004), Vancouver, Canada	Hospitalization by asthma	Children aged 6 to 12 years old	CO, SO_2, NO_2, O_3, monitoring sites	Average household income	Community	Risk of asthma hospitalization higher in children living in lower-SES areas. Risk modification by SES was divergent due to pollutants and lags
Lee et al. (2006), Seoul, South Korea	Hospital admission by asthma	Children under 15 years old	PM_{10}, SO_2, NO_2, CO, O_3, monitoring sites	Average health insurance rate	Community	Effect modifier statistically significant by health insurance. Relative risk of hospitalizations larger in lower-SES districts
Lin et al. (2008), New York City, USA	First admission by asthma	Children aged 1 to 6 years old	O_3, monitoring sites	Race, health insurance education level, living under the poverty level	Individual	Significant effect modifier by health insurance, education, poverty. Patterns of higher OR were reported in low-SES areas
Burra et al. (2009), Toronto, Canada	Medical visits by asthma	Children aged 1 to 17 years old	$PM_{2.5}$, SO_2, NO_2, O_3, monitoring sites	Mean income household	Community	Heterogeneous results for the effect modifier by income. Larger effects for low-socioeconomic groups were significant for NO_2 and $PM_{2.5}$
Delfino et al. (2009), California, USA	General hospital admission and emergency room visit by asthma	Children aged 0 to 18 years old	NO_x and CO; California Line Dispersion Model (CALINE4)	Household income, living in median or below poverty line, insurance status	Community	Higher effects in block groups with more families at the poverty level. Household income showed higher HR for strata greater than the median. No significant effect modification by health insurance
Hoffmann et al. (2009), Westphalia, Germany	Respiratory infections, allergic diseases, laboratory test (lung function, and allergic sensitization)	Preschool children	Total suspended particles; small-scale interpolation model	Migratory status, education level, household income, poverty line, unemployment	Individual	Heterogeneous results were found. Higher effects in high SES measured by education level. Higher effects among unemployed population for respiratory infections and abnormal lung function measured by health outcome
Shankardass et al. (2009), Southern California, USA	Asthma (new onset in a cohort study)	Preschool children	NO_x as a proxy for traffic-related air pollutants (TRAP); California Line Dispersion Model (CALINE4)	Psychosocial stress, parent's education level	Individual	Higher effects associated with TRAP for high parental stress compared to subjects with low parental stress. For parental education, the HR was higher for low-SES strata. Significant effect found in both variables for low-SES strata
Grineski et al. (2010), Arizona (Phoenix), USA	Hospitalizations by asthma (at least one night)	Children fourteen years old or younger	NO_2, monitoring sites	Insurance status and race	Community	Insurance status and race are modifiers of the impact of NO_2 on the risk of asthma hospitalizations. A greater effect in low-SES strata

Table 1 (continued)

Reference, location	Health outcomes	Age group	Air pollutant/exposure method	SES measurement	Level	Main results
Ebisu et al. (2011), Connecticut, USA	Wheeze symptoms (0, < 30 and > 30 days)	Children aged 0 to 4 months old	NO_2, monitoring sites and land-use regression	Family income and maternal educational attainment	Individual	SES can modify the effect of urbanity on health. Effects between urban land-use and severity of wheeze differed by SES, with higher effects in lower-SES areas
Cakmak et al. (2016), Windsor, Canada	Cough without cold, chest congestion, asthma, wheeze with dyspnoea, chest illness	Children in the fourth and sixth grades	SO_2, NO_2, $PM_{2.5}$ (TRAP); land-use regression, traffic density parameters	Income and education (parental/family)	Individual	Effects associated with exposure to traffic and respiratory symptoms were higher in low-SES groups when measured by education and income but not significant. Greatest effects for chest congestion, wheeze with dyspnoea and chest illness
Alwahaibi and Zeka (2016), Oman	Daily patient visits for acute respiratory diseases (ARD) and asthma	Individuals aged 0 to 20 years old	Industrial pollution; proximity model	Education level, employment status	Community	Higher effects in the lower strata with a higher percentage of the population without education and with unemployment. Effect modifier significantly increased the risk in both low- and high-SES strata
Yi et al. (2017), Seoul, South Korea	Allergic symptoms for atopic eczema, asthma, allergic rhinitis	Children aged 1 to 12 years old	TRAP, proximity density of vehicles on major roads	Monthly household income, economic strata of residence area	Individual	Heterogeneous results were reported by health outcome. Asthma and allergic rhinitis show a pattern of higher effect for low-SES households and regions

modification in the risk level was higher for low-SES groups than for high-SES groups. An exception was found in Wilhelm et al. (2009).

Despite the lack of consistency in the results, all authors identify SES as a factor that increases the vulnerability to air pollution. Seven of the 12 studies that used a single-indicator variable and two of the five studies that used a composite index found significant associations. The composite indices yielded more consistent results than the single-indicator variables. Notwithstanding, individual variables of the structural type, such as education level and insurance status, reflected significant associations and substantial differences in effect size among the SES strata. Based on the effect sizes, studies using education level as a SES measurement showed that the difference in risk between the low- and high-SES groups was 0.52 (Cakmak et al. 2016), 0.4 (Alwahaibi and Zeka 2016) and 0.35 (Shankardass et al. 2009), respectively. Concerning insurance status, the three highest differences were 0.2, 0.16 and 0.15 (Lee et al. 2006). Among the composite indices, the NDI reported wider differences between the strata compared to the others, such as the Townsend index. On the other hand, the smallest differences in the effect size were 0.001 and 0.002 (Burra et al. 2009; O'Lenick et al. 2017a) for income and the Townsend index, respectively. The effect sizes are presented in Table S1 (Supplementary Material).

Exposure assessment: influence of the exposure estimation in the identification of the effect modifier

Seven of the 17 analysed studies included statistical models to estimate exposure; ten included spatial analysis. A multi-pollutant evaluation was conducted in nine studies. Exposure to NO_2/NO_X was the most evaluated (11),

Table 2 Effect modifier evaluated through composite indices of socioeconomic status (SES) in North America from 2000 to 2017

Reference, location	Health outcomes	Age group	Air pollutant/exposure method	SES measurement	Level	Main results
Wilhelm et al. (2009), California (L.A.), USA	Asthma with or without attacks	Children aged 0 to 17 years old	PM_{10}, CO, NO_2, O_3, monitoring sites	Individual (child's insurance status); family (income, education, employment); neighbourhood (social cohesion)	Individual and community	Psychosocial factors modified the effect of O_3 exposure on risk of asthma. A higher effect was observed in high-SES strata. No significant effect modification when measured by child's insurance status, and education level
Shmool et al. (2014), New York City, USA	Emergency department (ED) visits by asthma	Children aged 0 to 14 years old	NO_2; New York City Community Air Survey with land-use regression	Psychosocial stress (violence, crime, abuse), education level, unemployment, income and overcrowding	Community	Heterogeneous results. Effect modifier in the NO_2–asthma exacerbation was significant for Factor 2 (crowding and poor access to resource, including healthcare indicators). Slight modification in the effect by Factor 1 (psychosocial stress). No significant effect modification by poverty rates
Yap et al. (2013), South Coast California, USA	Hospital admission for acute respiratory infections, pneumonia, asthma	Children 1 to 9 years old	$PM_{2.5}$, monitoring sites	Townsend index	Community	Consistency of the effect modifier is variable by region and health outcome. The South Coast areas present greater effects in lower SES (Townsend index score)
O'Lenick et al. (2017a), Atlanta, USA	ED visits for asthma and wheezy	Children aged 5 to 18 years old	$PM_{2.5}$, NO_2, O_3, elemental carbon, monitoring sites	Education, income, poverty, unemployment, the NDI and the Townsend index	Community	Identified a pattern of modification on the risk due to SES (education level). Higher effects in low-SES strata. Effect modification by the NDI and Townsend index was significant and higher in low-SES strata except for O_3
O'Lenick et al. (2017b), Atlanta, Dallas, St. Louis, USA	ED visits for respiratory diseases	Children aged 5 to 18 years old	O_3, monitoring sites	Education, living below the poverty line, the NDI	Community	Found evidence of effect modification. Significant effect modification by education, poverty and the NDI with higher effects in the low strata in each city

followed by ozone (7), $PM_{2.5}$ (4), proxy measures for industrial and TRAP (4), CO (4), SO_2 (4) and PM_{10} (1). Significant associations were obtained in five studies that used time-series analyses and four that used dispersion models. The studies that found a significant role of SES as an effect modifier in the children's respiratory outcomes tended to use finer temporal (Lee et al. 2006; Lin et al. 2008; Grineski et al. 2010) and spatial scales (Delfino et al. 2009; O'Lenick et al. 2017a) than those of other studies. A few studies assigned similar aggregation units for exposure and SES measurements.

We explored the differences in the effect sizes through OR, risk (RR) and hazard ratios (HRs), according to the SES measurements, for the most frequently evaluated pollutants in the 12/17 papers that reported them numerically. Figures 2, 3 and 4 only include asthma-related outcomes because there are a sufficient number of studies available. The effects on the association proximity to industrial zones, TRAP and asthma are presented in Fig. S1 (Supplementary Material). Additional health outcomes considered in the reviewed studies are displayed in Fig. S2 (Supplementary Material).

Fig. 2 Socioeconomic status (SES) as an effect modifier for associations between exposure to ozone and asthma-related outcomes in children in North America and South Korea from 2000 to 2017. *OR* Odd ratios, *RR* relative risk. *CI* 95% confidence interval

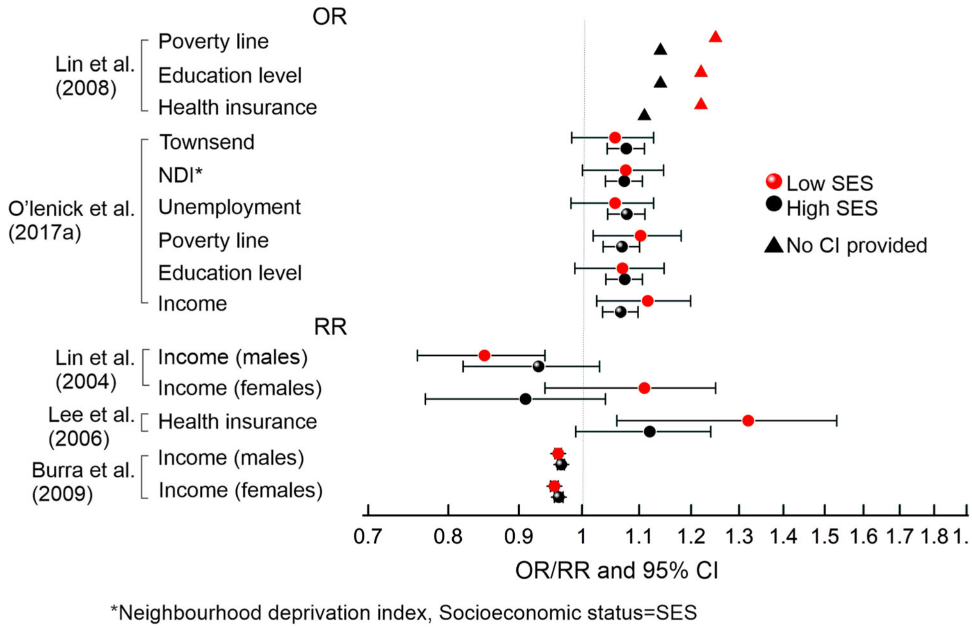
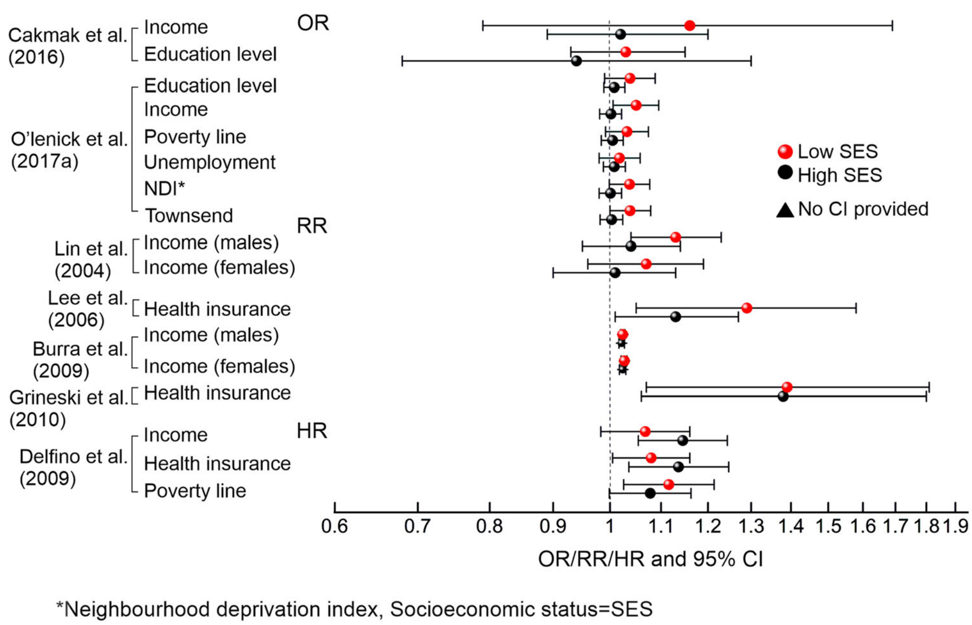
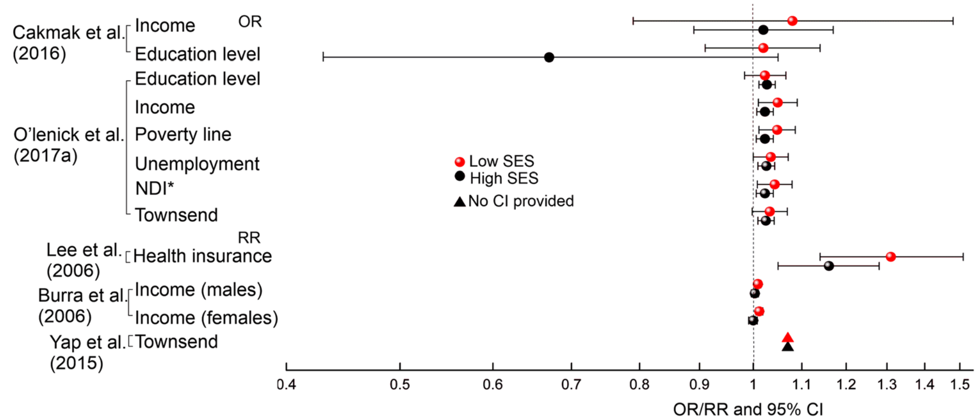


Fig. 3 Socioeconomic status (SES) as an effect modifier for associations between exposure to NO_x, NO_2, traffic-related pollution and asthma-related outcomes in children in North America and South Korea from 2000 to 2017. *OR* Odd ratios, *RR* relative risk, *HR* hazard ratio. *CI* 95% confidence interval



The estimates on the role of SES as an effect modifier in the risk of asthma-related outcomes (hospitalizations, emergency visits, department visits and reports of symptoms) were statistically significant for exposure to O_3 in most cases (Fig. 2) among the five presented studies; however, divergent results were observed in the modification of risk due to income (Lin et al. 2004; Burra et al. 2009). The most considerable effect was observed for the low-SES strata using health insurance as the SES measurement (Lee et al. 2006). This tendency was also observed for education level (Lin et al. 2008; O'Lenick et al. 2017a), with a statistically significant effect (Lee et al. 2006; Lin et al. 2008).

Reports for NO_x/NO_2 exposure (Fig. 3) showed narrower CIs, mainly when using composite SES indices (O'Lenick et al. 2017a) and income (Burra et al. 2009). In most instances, the low SES was identified as effect modifier which leads to a greater risk of asthma in children. Once again, the individual variables, such as medical insurance or parental education level, demonstrated more considerable differences between the strata than the other SES measurements (Lin et al. 2004; Lee et al. 2006; Cakmak et al. 2016). An exception was found in Grineski



*Neighbourhood deprivation index, Socioeconomic status=SES

Fig. 4 Socioeconomic status (SES) as an effect modifier for associations between exposure to $PM_{2.5}$ and asthma-related outcomes in children in North America and South Korea from 2000 to 2017. *OR* Odd ratios, *RR* relative risk. *CI* 95% confidence interval

et al. (2010), where smaller differences between strata were reported. The exposure estimation methods used in these studies did not seem to influence the finding of a statistically significant effect modification through SES strata.

In Fig. 4, we summarize the results from four studies focussed on $PM_{2.5}$ and one that assessed PM_{10} exposure (Lee et al. 2006). The analysed papers reported mixed results on the significance of the effect modification among SES strata; for O'Lenick et al. (2017a), Yap et al. (2013) and Lee et al. (2006), the results were significant for all SES indicators, while Burra et al. (2009) and Cakmak et al. (2016) found significance only for low-SES strata. Nevertheless, the results point in the same direction, increasing the risk in low-SES strata. The study by Cakman et al. (2016) reported the most substantial differences in risk between the strata when using education as a family-level variable and estimating $PM_{2.5}$ exposure by land-use regression models and traffic density parameters. Using composed indices yielded narrower CIs and higher consistency on the effect modifier identified among strata.

The reports of three papers that used proxy measures of exposure to fixed and mobile sources (Cakmak et al. 2016; Yi et al. 2017; Shankardass et al. 2009) are displayed in Table S2.

(Supplementary Material) and exhibited heterogeneous statistical significance. Differences in exposure assignment using individual/residential versus neighbourhood levels may explain this heterogeneity. However, both the OR and RR measurements show a clear pattern: Children living in low-SES strata had an increased risk of asthma due to SES.

Four papers evaluated exposure from mobile sources through dispersion models (Shankardass et al. 2009; Delfino et al. 2009) and parameters such as proximity and density of major roads (Cakmak et al. 2016; Yi et al. 2017). Significant associations with this exposure assessment and low education levels were reported by Cakmak et al. (2016) and Shankardass et al. (2009). However, Yi et al. (2017) reported heterogeneous results using major road density, income as an indicator of SES and different health outcomes. Although these variables of exposure provide precise information on children's exposure, in many cases, the SES information covered a larger scale. These aspects possibly contribute to the heterogeneity in the results.

Most of the studies considered in the previous section concluded that exposure to outdoor air pollutants has a significant effect on low-SES children, regardless of the analysed pollutant. The models used to estimate the exposure could influence the identification of SES as an effect modifier, mainly when the aggregation assigned to the exposure differs from the one assigned to the SES measurement.

Health outcomes

Regarding the respiratory health outcomes included in this review, six studies relied on information obtained directly through questionnaires and laboratory testing, while the remaining 11 used information from health information systems, hospital records and health insurance databases. Asthma was the most evaluated outcome (14); either individually (9) or in conjunction with acute respiratory infections (5). Only three studies evaluated upper and lower respiratory infections, including wheeze, allergies and lung function.

Interesting results were found in two studies that evaluated different health outcomes using individual self-report data and laboratory testing (Hoffmann et al. 2009; Cakmak et al. 2016). When using the self-reported health outcomes, the estimated risk measures were more extensive in the high-SES strata for allergic, respiratory diseases and cough without cold. When using laboratory tests for abnormal lung function and chest illness, the higher risks were found for the low-SES strata.

In the four studies that assess different health outcomes, namely Hoffmann et al. (2009) (allergic diseases, respiratory infections, markers of allergic sensitization, abnormal lung function), Alwahaibi and Zeka (2016) (acute respiratory diseases), Cakmak et al. (2016) (cough without cold, chest congestion, current asthma, wheeze with dyspnoea, wheeze, chest illness) and Yi et al. (2017) (asthma, allergic rhinitis), the reported results were heterogeneous. Hoffmann et al. (2009) and Alwahaibi and Zeka (2016) found a significant association in the combined effects for acute respiratory and allergic diseases, while Cakmak et al. (2016) only found associations with chest congestion. In Yi et al. (2017), there was not a clear pattern.

Discussion

In this review, we explored the existing published evidence of SES as an effect modifier in the relationship between air pollution-related children's respiratory health. We found a statistically significant effect-modifying role in nine out of the 17 studies. These studies showed a higher modification in the risk measure for lower socioeconomic groups, but the modification was not uniform.

The role of SES as an effect modifier has often been based on parent's information. Measures such as household income, insurance status and parental education level remain the most used despite the initiatives to look for a more child-oriented specific indicator, as presented in "The Global Initiative on Children's Environmental Health Indicators" (Kessler 2014; Wendee 2018; WHO 2004). Since 2009, there has been an increase in the number of studies devoted to obtaining SES information at the individual level, looking to give more emphasis to information that focuses on children (Hoffmann et al. 2009; Shankardass et al. 2009; Wilhelm et al. 2009; Ebisu et al. 2011; Cakmak et al. 2016; Yi et al. 2017).

The lack of consistency in the results exploring the role of SES as an effect modifier of pollution-related health effects has been explored in systemic reviews (Vinikoor-Imler et al. 2014; Rodríguez-Villamizar et al. 2016), where evidence seems to be weak. In this paper, we found evidence that points towards an increased risk for children in low-SES groups. However, the results are not unanimous, and the measures to evaluate SES may act differently from one health outcome to another. In addition, the exposure metrics and the aggregation of the data have an important role. Attention to these issues is necessary to understand the strength of the effect modification reported for these conditions.

Selection of SES measurement

There is controversy over which SES indicator better reflects health outcome disparities, and our literature review found gaps related to the chosen measure. The chosen SES measurement should not be entirely defined by the statistical significance; it must be carefully selected. Houweling et al. (2003) pointed out that the choice of SES measurement often affects the estimates of the health outcomes and the differences reported between countries or time intervals.

In comparative studies between regions, even if the selected SES measurements are similar, they can lead to different results (Yap et al. 2013; O'Lenick et al. 2017b). The geographical, climatic, political and cultural factors could influence these differences. Additionally, theoretical support concerning the correlation with the health outcomes, the differentiation between direct and indirect measures of SES and the inclusion of both single-indicator variables and composite indices are necessary to consider when designing a study (Wagstaff and Watanabe 2003; Van Vuuren et al. 2014). We considered that the selected SES measurement should capture the relevant conditions for children related to their care and activities that may lead to increased exposure to air pollutants. For example, in single-variable analyses, income showed heterogeneity in the significance of the effect modifier. The authors recognized that using it may overlook some other factors that interact in socioeconomic status and attenuate the effects seen (Lin et al. 2004; Cakmak et al. 2016).

Regarding composite indices, Oakes and Rossi (2003) mentioned that although separate variables are preferred for statistical modelling, composite indices (which condense a large quantity of information) have advantages in stratified analysis and the communication of results. In this review, we identified that the results from papers using composite indices showed narrower confidence intervals and high consistency in the differential effects between the SES strata than studies using a single-indicator variable.

Measurement units

The current evidence showed another gap related to the scales used for exposure assignment; in this sense, there is consensus, i.e. the higher the resolution used for the geographical and temporal analysis is, the more precise the approximations will be.

When using data from monitoring sites in bulk/average over a large geographical area, such methods overlook the different sub-regional levels of exposure at the municipal level; this is known as the modifiable areal unit problem (MAUP) (Maantay 2007). As we noted in the reviewed studies (Shankardass et al. 2009; Ebisu et al. 2011; Cakmak et al. 2016), similar levels of aggregation between the spatial units assigned to the exposure and the SES measurements can contribute to a more precise estimate of the modifying effect of SES.

Another gap exists concerning the exposure measured through proxies such as traffic density. Children living within the same distance to large roads may be exposed to different levels of TRAP depending on the built environment and geographical characteristics of each place (Yi et al. 2017).

On the other hand, the presented results concerning exposure to $PM_{2.5}$ did not analyse information about its composition. Such characterization could contribute to the overall analysis by integrating the socioeconomic measures with $PM_{2.5}$ exposure (Bell and Ebisu 2012) and considering the relationship between the toxicity of specific components and personal exposure (Peng et al. 2009; Lippmann et al. 2013), which can significantly differ in intra-urban levels (Kassomenos et al. 2014).

Information on health outcomes

Overall, SES measurements assessed in low strata evidenced a significant effect modifier role on asthma, acute respiratory infections, chest congestion and combined effects related to outdoor air pollution. However, there was no definitive consensus, as heterogeneity was observed in the statistical significance and the direction of the effect; for example, a more substantial effect on the high-SES group was found in the studies of Lin et al. (2004) and Yi et al. (2017) compared to those that found a more substantial effect on the low-SES group.

Health outcomes assessed by questionnaires about asthma, allergic diseases and registered asthma hospitalizations displayed certain results. For the low-SES population, a considerable number of less severe cases are either not reported in questionnaires or not receive medical attention; only the severe cases are notified (Corburn et al. 2006; Hoffmann et al. 2009; Wilhelm et al. 2009). Therefore, it is difficult to determine the prevalence of such cases in the low-SES groups.

These differences in health outcomes are also observed depending on the use of self-report data and laboratory testing. Significant associations were found when using laboratory testing, in contrast to self-report data (Wilhelm et al. 2009). Under-reporting in low-SES strata may be associated with education or cultural factors; however, an explanation for these differences remains scarce. Selection bias, subject-based reporting bias and biologic interaction were noted by Hoffmal et al. (2009) and Maantay (2007).

Additionally, the results pointing high-SES as an effect modifier of the risk of asthma and allergic diseases have suggested the hygiene hypothesis as a potential mechanism for lower incidence in children living in low-SES strata. This hypothesis related the prenatal and early childhood exposure to viruses, bacteria and endotoxins from older dwellings and overcrowded conditions as factors against the sensitization of these diseases (Corvalán et al. 2005; Uphoff et al. 2015). The evidence for this outcome has been controversial and requires a deeper understanding of the contextual differences and long-term assessments.

Further work requires better integration of data and theorization based on different disciplines. Transdisciplinary research can contribute to offering a broader perspective of the links between social, economic and ecological systems and including the knowledge and perception of the community, to have a better understanding of behavioural and contextual factors that lead an increased exposure of children living in poor conditions. This research would provide valuable support for the interventions of public policies to reduce air pollution considering equity, which, according to Benmarhnia et al. (2014), persists as a challenge in evidence-based public health.

An important fact is that most studies included in this review are from developed countries, thus highlighting the necessity to evaluate SES, as an effect modifier of the risk of health outcomes in developing nations. Nonetheless, challenges to this evaluation are in place, such as the limited number of monitoring stations, the lack of knowledge about the air quality status in many cities, the lack of robust epidemiological and poverty surveillance systems, and pronounced inequalities.

Conclusion

This scoping review summarized the evidence on the complex relationship between children's respiratory health and outdoor air pollution exposure modified by SES. A statistically significant effect was found in nine out of the 17 studies. Associations between respiratory health outcomes, mainly children's asthma, and ambient pollutants yield a tendency of larger effects in low-SES groups, but the results are not consistent.

We found mixed results related to the lack of convergence among the temporary or spatial units assigned to the exposure, the SES measurements and the source of information on the health outcomes. These factors possibly influence underestimation or generalizations that go beyond the specific context.

The majority of the studies used a structural SES variable; income was the most frequently employed and provided heterogeneous results. Indicators such as parental/maternal education level and insurance status showed more sensitivity and clearer patterns when detecting the SES effect modification for children in low-SES strata. Composite indices were often used to explore the effect modifiers between cities but without a definitive consensus.

The complexity of analysing socioeconomic status, health outcomes and exposure suggests the need to explore these aspects from different disciplines, including new qualitative and quantitative data collections, mainly in regions that face vast economic inequalities and poor air quality and where studies remain scarce.

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