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Social inequalities resulting from health risks related to ambient air quality—A European review

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Background: Environmental nuisances, including ambient air pollution, are thought to contribute to social inequalities in health. There are two major mechanisms, which may act independently or synergistically, through which air pollution may play this role. Disadvantaged groups are recognized as being more often exposed to air pollution (differential exposure) and may also be more susceptible to the resultant health effects (differential susceptibility). **Method:** European research articles were obtained through a literature search in the Medline database using keywords 'Socioeconomic Factors, Air Pollution, Health' and synonymous expressions. **Results:** Some studies found that poorer people were more exposed to air pollution whereas the reverse was observed in other papers. A general pattern, however, is that, irrespective of exposure, subjects of low socio-economic status experience greater health effects of air pollution. So far as we are aware, no European study has explored this relationship among children. **Conclusion**: The housing market biases land use decisions and may explain why some subgroups suffer from both a low socio-economic status and high exposure to air pollution. Some data may be based on inaccurate exposure assessment. Cumulative exposures should be taken into account to explore health problems more accurately. The issue of exposure and health inequalities in relation to ambient air quality is complex and calls for global appraisal. There is no single pattern. Policies aimed at reducing the root causes of these inequalities could be based on urban multipolarity and diversity, two attributes that require long-term urban planning.

Keywords: air pollution, environmental inequalities, health inequalities, social determinants

Introduction

There is now clear evidence of social inequalities in health in most industrialized countries:[1] in general, socio-economically disadvantaged people are more strongly affected by various health problems[2–4] than more affluent ones. Despite numerous factors already identified, some of these inequalities remain unexplained, leading to the hypothesis that environmental nuisances may also contribute to social health inequalities.[5,6] Assessing how environmental exposure may partly explain such inequalities is a major subject of public health research.

According to the literature,[5,6] there are two major mechanisms that may act independently or together, through which environmental exposure may contribute to social health inequalities. (i) Among the general population, disadvantaged groups are recognized as being more often exposed to sources of pollution (*differential exposure*), a situation that contradicts the principle of *environmental equity*, according to which no group of people should bear a disproportionate share of harmful environmental exposure. (ii) The general population may also be more likely to exhibit resultant health effects (*differential susceptibility*). To investigate this hypothesis, studies explored the assumption that exposure to environmental nuisances might give rise to greater health effects among socioeconomically disadvantaged groups; this issue of greater vulnerability is less well documented.

Many epidemiological studies, mostly in North America and in Europe, have demonstrated that both short- and long-term exposures are associated with several health events. In spite of the improvement of air quality during the recent decades, air pollution remains a major field for investigation and action in view to improving public health in Europe. In this context, this review deals with European studies that concern two issues: whether subjects or populations of poor socio-economical status (SES) live in areas with lower ambient air quality than richer ones; and whether the association between ambient air pollution and health is influenced by the SES assessed at an individual or ecological level.

Methods

European research articles were obtained through a literature search in the Medline database of the National Library of Medicine. Only articles written in English or in French were selected, up to the end of April 2009.

Three principal MeSH-terms were used for the literature search queries: 'Europe AND socioeconomic factors AND air pollution'. Numerous synonymous expressions of these two keywords were also used, such as 'social class, unemployment, income' for socio-economic factors and 'ozone, nitrogen dioxide, sulphur dioxide, carbon monoxide, particulate matter' for air pollution. We have also included more general expressions, environmental justice and environmental inequity dealing with the socio-environmental disparities. Were excluded papers investigating only indoor air pollution and occupational or exposure to environmental tobacco smoke. Were also excluded papers in which air pollution exposure was measured using a proxy-indicator such as distance to high traffic roads or to industrial plants, and papers where no result was presented on either

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socio-economically based 'differential exposure or differential susceptibility'.

Concerning the assessment of differences in response to exposure according to SES, were also excluded all papers which did not formally test this effect modification, either by a stratified analysis or through the introduction of an interaction term in some regression model. Studies where the SES was merely considered as a confounder were thus discarded.

The results section is structured according to the two mechanisms through which environmental exposure may contribute to social health inequalities, namely differential exposure and differential susceptibility. Papers are sorted according to the country where the study was conducted.

Results

A total of 129 papers assessed inequalities in exposure in Europe according to some measure of socio-economic status, and 23 explored the modification of the relation between air pollution and some health event, often mortality, by the socio-economic status. They are described in tables 1 and 2 that provide information on the study design, how exposure and SES were assessed and key results. Additional information is given in table 2 on the health events and the methods used to assess effect modification.

Differential exposure

The majority of European studies took place in the UK. In England and Wales, McLeod in 2000[7] investigated the relationship between PM_{10}, NO_2 and SO_2, and socio-economic indicators. They found that higher social classes were more likely to be exposed to greater air pollution, whatever the pollutants and the socioeconomic indicators they used. In contrast, Brainard *et al.*[8] found that the level of NO_2 and CO in Birmingham was higher in communities with a greater proportion of coloured people and deprived classes. Several years later, in Leeds, Mitchell[9] demonstrated social inequality in the distribution of NO_2 according to the Townsend index. Comparing the trend of NO_2 levels between 1993 and 2005, they demonstrated that the average difference between deprived and affluent communities declined from 10.6 $\mu g/m^3$ in 1993 to 3.7 $\mu g/m^3$ in 2005 as a result of city-wide improvements in air quality driven by fleet renewal. Wheeler and Ben-Shlomo,[10] also found in 2005 that air quality is poorer among households of low social class. More recently, social inequalities in NO_2 levels in Leeds were confirmed by Namdeo and Stringer[11] at the detriment of poorer groups. In London, a comparison before and after the introduction of the Congestion Charging Zone showed that, although air pollution inequalities persisted, there was a greater reduction in air pollution in deprived areas than in the most affluent ones.[12] Briggs *et al.*[13] concluded that the strength of the association of the deprivation index with air pollution tended to be greater than for other environmental nuisances.

Two studies were conducted in Oslo, Norway. Irrespective of the socio-economic indicators they used, Naess *et al.*[14] showed that the most deprived areas were exposed to higher $PM_{2.5}$ levels and revealed a clear dose–response relationship between $PM_{2.5}$ levels and the number of subjects living in flats. In contrast, no association between NO_2 levels and education or occupation was found in the cohort of Norwegian men.[15]

Within the EXPOLIS study, environmental inequalities arising from personal exposure to NO_2 and $PM_{2.5}$ were explored in Helsinki, Finland.[16,17] Personal levels of NO_2 decreased with a higher level of education. Much greater contrasts in exposure were observed between socio-economic groups for men than for women, both for NO_2 and $PM_{2.5}$. While the occupational status was not correlated with $PM_{2.5}$ globally, a stratified analysis by gender showed a strong association for men only: the mean $PM_{2.5}$ exposure was ~50% lower among white-collar workers than among the other occupational categories.

Two studies conducted in Sweden brought evidence of social inequalities related to NO_2. Stroh *et al.*[18] found that the strength and direction of the association between the socio-economic status and NO_2 concentrations varied considerably between cities. In another study, children from areas with low neighbourhood socio-economic status were shown more exposed to NO_2 both at home and at school.[19]

We found four other European studies that explored social inequalities related to air pollution. In Rijnmond (The Netherlands), according to Kruize *et al.*,[20] lower income groups live in places with higher levels of NO_2 than greater income groups. In a cohort of German women, Schikowski *et al.*[21] revealed the existence of a social gradient with higher PM_{10} exposures among subjects with <10 years of school education than among those with higher education. Inversely, in Rome, Italy, the higher social class appeared to reside in areas with high traffic emissions; this disparity was even stronger when SES rather than income was considered.[22] Using a French deprivation index and a fine census block resolution scale,[23] Havard *et al.*[24] found, in Strasbourg, France, that the mid-level deprivation areas were the most exposed to NO_2, PM_{10} and CO.

Differential susceptibility

Few studies have been published on the role of SES in the relationship between air pollution and health in Europe. In Rome,[22] social class clearly affected the relationship between PM_{10} and mortality: the upper social classes were not as affected by the harmful effects of air pollution as those in lower social classes. Since the former live in areas with higher air pollution, the authors interpreted their findings in terms of differential susceptibility. Supporting this hypothesis, they found a higher proportion of chronic diseases among the poor. They also argued that living in an area with a high level of air pollution, mainly in the city centre, did not necessarily result in greater exposure. Wealthier residents of Rome were said to spend less time in their homes than poorer social groups because they were more likely to have second residences outside the city.

In four Polish cities, Wojtyniak *et al.*[25] showed a significant association between exposure to black smoke and either non-trauma or cardiovascular mortality among subjects who had not completed secondary education. Significant associations between SO_2 or NO_2 and cardiovascular mortality were also present more particularly among subjects aged >70 years with education below secondary school level.

Finally, in France, five studies investigated the impact of the socio-economic level on air pollution effects. In Bordeaux, Filleul *et al.*[26] found a significant association between mortality among people aged >65 years and exposure to black smoke among blue-collar workers only. Also in Bordeaux, however, a cohort study[27] comparing the characteristics of people who died on days when the highest and the lowest black smoke concentrations were observed, did not found modification of the effect of air pollution on mortality by the SES. In Strasbourg, two studies explored the air pollution effects on myocardial infarction events[28] and on asthma attacks.[29] Results from the former supported the hypothesis that neighbourhood SES may modify the acute effects of PM_{10} on the risk of MI: differential susceptibility

Table 1 European Studies investigating the environmental inequalities regarding air pollution exposure

Authors	Population/country	Study design[a]	Air pollution variables[b]	Geographical level and SES variables	Main results
Brainard *et al.*[8]	Birmingham, England	Geographical	Annual average hourly CO and annual (hourly) NO_2	At a enumeration district scale (medium population of 496 residents): ethnicity, male unemployment, households without a car, homeowners, pensioners, social class, deprivation index (carstairs, Jarman and Townsend)	The average CO and NO_2 emissions for districts with deprived populations are higher than in affluent ones: 2331 vs. 2112 $\mu g/m^3$ and 23.71 vs. 22.29 $\mu g/m^3$, respectively. The averages of these pollutants were also higher among districts with high proportion of blacks than among more white districts: 2919 vs. 2276 $\mu g/m^3$ for CO and 27.09 vs. 23.32 $\mu g/m^3$ for NO_2.
Briggs *et al.*[13]	England	Geographical	Annual average of NO_2, PM_{10}, O_3 and SO_2	Three geographical levels of analysis: super output areas (SOAs, an average of 1500 persons), wards (aggregations of SOAs, an average of 6200 persons) and districts (an average of 139,000 persons). Several indicators of deprivation: index of multiple deprivation: income, employment, education and access to housing and services	Positive correlations (varying around 0.3 and 0.2 at SOA and ward geographical scale) are found with all the air pollutants (except O_3): a high level of air pollution was associated with a high level of deprivation (inverse relation for O_3). Variation of the association strength was observed according to the geographical scale
Chaix *et al.*[19]	Children aged 7–15 years, Malmo, Sweden (2001)	Multilevel	Annual average of NO_2 estimated for the points of the 100 metre grid that were the closest to the building of residence and school of attendance	Annual mean of income of subjects aged $\geq$25 years in each residential building where children in the study lived in 2001 and in each neighbourhood of residence. The median number of people aged 25 years or older in buildings of residence was 2 and it was 1484 in neighbourhoods of residence.	Children from low SES neighbourhoods were more exposed to NO_2, both at their residence place (21.8 vs. 13.5 $\mu g/m^3$ for the lowest and the highest income classes, respectively) and at school (19.7 vs. 13.7 $\mu g/m^3$).
Forastiere *et al.*[22]	Only residents of Rome aged 35 years and older (1998–2001)	Geographical	PM, CO, NO_x, Benzene	Estimation at census block scale (480 inhabitants on average) of a median per capita income index and a socio-economic index (SES, including educational level, occupational categories, working-age unemployment rate, family size, crowding and proportion of dwellings rented/owned)	Concentrations increase with the average block income level for all traffic pollutants (PM: 16.7 vs. 21.7 $\mu g/m^3$, for the low- and high income categories, respectively; CO: 10.4 vs. 24.3 $\mu g/m^3$; NO_x: 10.4 vs. 26.7 $\mu g/m^3$; Benzene: 10.7 vs. 25.2 $\mu g/m^3$). Environmental inequalities are stronger using the SES index (PM: 9.2 vs. 39.6 $\mu g/m^3$, CO: 6.8 vs. 45.3 $\mu g/m^3$, NO_x: 11.2 vs. 41.6 $\mu g/m^3$, Benzene: 7.5 vs. 46.2 $\mu g/m^3$).
Havard *et al.*[24]	Strasbourg, France	Geographical	Annual average of NO_2	At a French census block scale (2000 inhabitants in average): socio-economic index (including 19 socio-economic and demographic variables)	There was an association between deprivation index and NO_2 levels: the mid-level deprivation areas were the most exposed (39.6 $\mu g/m^3$) whereas the most affluent areas were the least (30.6 $\mu g/m^3$). Same relations were observed with SO_2 and $PM_{10,}$ but inverse relationship with O_3.
Kruize *et al.*[20]	Rijnmond Region, Netherlands	Semi-Individual	Annual average of modelled NO_2 concentrations (25 $\times$ 25 m grid)	Income	There is a significant association between income and NO_2 level: the mean of NO_2 are 37.7 and 38.2 $\mu g/m^3$ for the higher and lower income categories, respectively.
McLeod *et al.*[7]	England and Wales	Geographical	NO_x, PM_{10}, SO_2	At local authority district scale and/or regional scale: social class index, population density and percentage of ethnic minorities.	The higher social classes are more likely to be exposed to greater air pollution, whatever the pollutant, the socio-economic indicator and the model that was implemented.
Mitchell *et al.*[9]	Leeds, UK	Geographical	Annual mean of NO_2	At a 200 m $\times$ 200 m cell level (3600 points spaced by 200 m intervals in a grid cell pattern throughout the 144 km^2 inner box): Townsend deprivation index	A clear association between deprivation and NO_2 level: in 2005, the mean of NO_2 is around 18 $\mu g/m^3$ for the most affluent areas vs. 22 $\mu g/m^3$ for the least ones.
Namdeo *et al.*[11]	Leeds, UK	Geographical	Annual mean of NO_2	At the Census Output Area level: cumulative deprivation index	Deprived population groups are disproportionately exposed to higher NO_2 level as compared with the affluent group: a scenario gives for example, 20.5 $\mu g/m^3$ vs. 19.2 $\mu g/m^3$, respectively.

(*continued*)

Table 1 Continued

Authors	Population/country	Study design[a]	Air pollution variables[b]	Geographical level and SES variables	Main results
Naess *et al.*[14]	General population aged 50–74 years residing in Oslo, Norway on 1 January 1992	Multilevel	Average monthly concentrations of $PM_{2.5}$ during period 1992–95	Social deprivation at both individual and administrative neighbourhood levels: education, household income, occupational class, ownership status of dwelling, type of dwelling and crowded households	There is a gradual increase of $PM_{2.5}$ when the proportion of subjects living in a flat increases across neighbourhoods (mean value of $PM_{2.5}$ ranging from 12.1 μg/m^3 in the lowest category to 17.0 μg/m^3 in the highest).
Rotko *et al.*[16]	Population aged 25–55 years, Helsinki (Finland)	Individual	48-h exposure of NO_2	Occupational status, education level and employment status	There is an association between personal exposure to NO_2 and education level: less educated subjects have higher exposures than educated ones (mean of NO_2 equal to 26.3 and 24.4 μg/m^3, respectively). The same association is seen according to the employment status among men
Rotko *et al.*[17]	Population aged 25–55 years, Helsinki (Finland)	Individual	48-h exposure of $PM_{2.5}$	Occupational status, education level and employment status	There is an association between personal exposure to $PM_{2.5}$ and education level: less educated subjects have higher exposures than educated ones (mean of PM2.5 equal to 18.98 and 13.41 μg/m^3, respectively). There is also an association between $PM_{2.5}$ and occupational status, with low exposures for white-collar employees compared to other categories (mean $PM_{2.5}$ levels are 11.97 and 20.46 μg/m^3, respectively). Stratification analysis by gender demonstrates that associations persist among men but not among women. For men, unemployment dramatically increases $PM_{2.5}$ exposure (41.8 vs. 15.5 μg/m^3).
Stroh *et al.*[18]	Scania, Sweden		Annual average NO_2 modelled with a 250 × 250 m grid resolution	Individual data: country of birth, education level	Strength and direction of the association between NO_2 and social categories varies within cities. In Malmö, subjects born in Sweden tend to live in areas with lower concentrations of NO_2 than those born in other countries. Inverse conclusions are drawn in other cities. The association between NO_2 and education ended show the same discrepancy between Malmö and the four other cities.
Schikowski *et al.*[21]	Women aged 55 years at time of investigation, Ruhr, Germany	Semi-Individual	PM_{10}, NO_2 and TSP	Education level	Women with <10 years of school education are more exposed to PM_{10} than those with a higher education level. No association has been found with NO_2.
Tonne *et al.*[12]	London, England	Geographical	Annual average NO_2 and PM_{10}	At census ward scale: index of multiple deprivation	The mean of PM_{10} and NO_2 increases from the less deprived neighbourhoods (C1, class 1) to the most ones (C5, Class 5): the mean for C1 and C5 are 38.1 and 46.7 μg/m^{3}for NO_2 and 25.7 and 27.5 μg/m^3 for PM_{10}, respectively.
Wheeler *et al.*[10]	General population aged 16–79 years, England	Semi-individual (household)	Index of air pollution combining annual average of NO_2, PM_{10}, NO_2 and Benzene estimated at a ward geographical level. The air pollution index of each participant is equal to the level of their residential ward	Social class of head of household	Environmental inequity is observed among urban households: air quality is poorer among households of low social class. There is a suggestion of inverse relationship for rural and semi-rural households.

a: CO, carbon monoxide; NO_2, nitrogen dioxide; O_3, ozone; PM, particulate matter; PM_{10}, particulate matter with an aerodynamic diameter of up to 10 mm; $PM_{2.5}$, particulate matter with an aerodynamic diameter of up to 2.5 mm; SO_2, sulphur dioxide; TSP, total suspended particulates.

b: Geographical: socio-economic status and air pollution exposure were both estimated at a same geographical level; semi-individual: socio-economic status and air pollution exposure were estimated at a individual and geographical level, respectively; individual: socio-economic status and air pollution exposure were both estimated at a individual level; multilevel: socio-economic status was estimated at both individual and geographical level whereas the air pollution exposure was estimated at geographical level.

Table 2 European Studies assessing the potential modification effect by the socio-economic status on the relation health and air pollution exposure

Authors	Population/country	Health variables	Air pollution variables[a]	Geographical level and SES variables	Methods to evaluate effect modification	Main results
Filleul *et al.*[26]	Residents of Bordeaux (France), population older than 65 years (1988–97)	Non-trauma and cardiorespiratory mortality	Daily mean of BS	At individual level: educational attainment (without primary school diploma, primary school diploma, secondary validated or higher) and previous occupation (never worked, white-collar, blue-collar)	Stratified analysis and test for heterogeneity	Increase in mortality for a 10 mg/m^3 increment in BS concentrations. Non-trauma mortality: only blue collars show a significant association: OR = 1.41 (1.05–1.90). Cardiorespiratory mortality: association is greater among subjects with high education: OR = 4.36 (1.15–16.54).
Filleul *et al.*[27]	Residents of Bordeaux (France), population older than 65 years (1988–97)	Non-trauma mortality	BS (above 90th percentile or below 10th percentile of observed ambient air concentrations)	At individual level: educational level (no school, primary without diploma, primary with diploma) and previous occupation (domestic employees and women at home, blue-collar workers craftsmen and shopkeepers, other employees and intellectual occupations)	Stratified analysis and test for heterogeneity	No effect modification according to socio-economic indicators.
Forastiere *et al*[22]	Residents of Rome (Italy) aged 35 years and older (1998–2001)	Mortality	Daily PM_{10}	Estimation at census block scale (480 inhabitants on average) of a median per capita income index and a socio-economic index (including educational level, occupational categories, working-age unemployment rate, family size, crowding and proportion of dwellings rented/owned)	Interaction term in multivariate model	Effect modification of socio-economic status on the PM_{10}-mortality association: the effect is stronger among people with lower income and SES (1.9 and 1.4% per 10 µg/m^3, respectively) compared with those in the upper income and SES levels (0.0 and 0.1% per 10µg/m^3, respectively).
Havard *et al.*[28]	Residents of Strasbourg (France), population aged 35–74 years (2000–03)	Myocardial infarction events	24-h average PM_{10} concentrations	At a French census block scale (2000 inhabitants on average): socio-economic index (including 19 socio-economic and demographic variables)	Stratified analysis and test for heterogeneity	Significant influence of neighbourhood SES, with greater effect of PM_{10} observed among subjects living in the most deprived neighbourhoods (20.5% increase, 95%CI: 2.2–42.0).
Laurent *et al.*[29]	Residents of Strasbourg (France), general population (2000–05)	Astham attacks	The daily air pollution indicator considered for PM_{10}, NO_2, and SO_2 was the 24-h average concentration. It was the maximum daily value of the 8-h moving average for the O_3.	At a French census block scale (2000 inhabitants in average): socio-economic index (including 19 socio-economic and demographic variables)	Stratified analysis and test for heterogeneity	Socio-economic deprivation had no influence on the association between air pollution and asthma attacks, whatever the pollutant.

(*continued*)

Table 2 Continued

Authors	Population/country	Health variables	Air pollution variables[a]	Geographical level and SES variables	Methods to evaluate effect modification	Main results
Laurent *et al.*[31]	Residents of Strasbourg (France), general population (2000–05)	β-agonist sales for asthma	The daily air pollution indicator considered for PM_{10}, NO_2, and SO_2 was the 24-h average concentration. It was the maximum daily value of the 8-h moving average for the O_3.	At a French census block scale (2000 inhabitants on average): socio-economic index (including 19 socio-economic and demographic variables)	Stratified analysis and test for heterogeneity	Socio-economic deprivation had no influence on the association between air pollution and asthma attacks, whatever the pollutant.
Wojtyniak *et al.*[25]	Two group of population (i) between 0 and 70 years and (ii) >70 years, residents of Cracow, Lodz, Poznan and Wroclaw (Poland)	Non-trauma and cardiovascular mortality	BS, NO_2 and SO_2 (day of death or preceding day)	Educational	Stratified analysis and test for heterogeneity	Non-trauma mortality: significant effect of BS among the less than secondary education group in both age groups. Significant effect of NO_2 in the oldest age group and for those below secondary education only. Significant effect of SO_2 in the oldest age group and those with less than a secondary education.Cardiovascular mortality: significant effect of BS only for those with less than a secondary education in both age groups. Significant effect of NO_2 for secondary education and above, only in the oldest age group. Significant effect of SO_2 only among subjects >70 years with below secondary education level.

a: BS, Black Smoke; NO_2, nitrogen dioxide; O_3, ozone; PM_{10}, particulate matter with an aerodynamic diameter of up to 10 mm; SO_2, sulphur dioxide.

was suggested as the more plausible explanation since these most deprived population did not live in the more polluted place.[30] On the other hand, socio-economic deprivation did not modify the relation between emergency telephone calls for asthma and concentrations of PM_{10}, SO_2 and NO_2;[28] this finding was confirmed using the number of β-agonist sales for asthma.[31]

Discussion

This literature review bears on the still small number of papers that investigated exposure and/or susceptibility differentials in Europe according to the socio-economical status, a rather recent topic that is yet less documented than in the USA and Canada. The European studies yield mixed findings regarding exposure disparities: in some instances, the association between air pollution and SES translates into poorer populations or areas being at greater exposure. Inversely, richer populations have been reported at greater exposure in other studies. However, beyond these variations, the general pattern in terms of health consequences is that deprived populations, although not always more exposed, experience greater harmful effects of air pollution, because of vulnerability factors.

In contrast, more discrepant results are observed in the non-European literature.

For example, among recent papers, the study by Charafeddine and Boden[32] in the USA found that subjects living in the most affluent counties with high particulate levels are significantly more likely to report fair or poor health, compared to those in poorer counties who experience exposure to the same air quality, whereas Zeka *et al.*,[33] in 20 US cities, showed stronger associations between PM_{10} and mortality for the less educated subjects (although not statistically significant). Similarly, poorer education was associated with a greater impact of air pollution on mortality in Shangai,[34] whereas the Chinese Longitudinal Health Longevity Survey[35] showed that elderly subjects living in more privileged urban areas were more affected by air pollution than their counterparts in more deprived ones. By the same token, Gouvenia and Fletcher[36] found in Sao Paulo, Brazil, a slightly increased risk of mortality associated with PM_{10} among elderly people living in the most privileged areas, while Martins *et al.*[37] in the same city showed that poorer areas presented the strongest association between PM_{10} and mortality among the elderly. Generalization from these partial observations is clearly premature. Absence of consensus as to the methodology used when investigating environmental and social inequalities (geographic unit, methods of statistical analysis, exposure assessment procedures and definition of deprivation) renders most of the results non-comparable and might explain part of these discrepancies.[38,39]

Nonetheless, several pathways and mechanisms are discussed in the literature to explain these social differences. Inequalities in environmental conditions are often put forward. Residential segregation may be one major reason why communities differ in their exposures. In Europe, socio-demographic disparities, notably those related to racial segregation, are less marked than in the USA; here, social and economic resources are the main determinants of environmental disparities. The housing market biases land use decisions and might explain why some groups of people suffer from both a low socio-economic status and bad air quality at their place of residence. One reason is that the presence of pollution sources depresses the housing market and provides an opportunity for local authorities to construct council housing at low cost.[40,41] Symmetrically, the presence of council housing in a given urban area tends to depress the price of land over time, encouraging the setting up of activities and facilities that generate pollution.

'Differential exposure' beyond ambient air quality might partly explain why health effects of air pollution might be different across social classes. Living in a residential area with high air pollution levels does not necessary cause greater overall exposure. Affluent people are likely to have second homes outside cities and they may, therefore, spend less time at their main residence. Not taking this into account could yield exposure misclassification in that, while more affluent social categories may tend to live in central, more expensive, areas with higher pollution in some cities, their true year long exposure is probably overestimated.[22] Conversely, subjects in deprived areas live in old dilapidated homes with poor ventilation and insulation, factors which favour the concentration of indoor pollutants. Moreover, they may be more likely to spend time close to or in the traffic, for example, working on the street rather than inside office buildings, or doing long commuting in public transport. Hence, the true daily and long-term exposures of these groups are probably underestimated. It is well documented that poorer people are more likely to suffer from several types of environmental exposure. In the German study by Schikowski *et al.*[21] the authors demonstrated that, in addition to the increase of PM_{10} levels with poorer education, the prevalence of occupational exposures and of current smoking followed the same gradient. Along the same line, Bell and Dominici[41] suggested that factors other than ambient air exposure, such as residential or occupational exposures, might explain why areas with a high Afro-American population proportion and high unemployment might exhibit a greater impact of air pollution in US cities.

People with a low SES may be more sensitive to air pollution-related hazards because of the high prevalence of existing diseases, an attribute which refers to 'differential susceptibility'. For example, Forastiere *et al.*[22] raised this hypothesis to explain their results, having excluded the causal pathway of inequalities in environmental quality. They found a higher prevalence of chronic conditions such as diabetes, hypertensive diseases and heart failure in low than in high-income groups. The former may receive inferior medical treatment for their conditions.[35] They may also have more limited access to good food, resulting in a reduced intake of antioxidant vitamins and polyunsaturated fatty acids that protect against adverse consequences of particle or ozone exposure. In the particular case of infant mortality, Romieu *et al.*[42] suggested that both micronutrient deficiencies and concurrent illnesses might decrease the immune response and make children more vulnerable to the adverse effects of air pollution.

It has been suggested that the presence of competitive risk factors in poorer areas might explain why health risks associated with air pollution may in some instances be greater among wealthier groups.[31,35] Some authors argue that poorer people are affected by many other risk factors that tend to increase mortality rates owing to other causes such as violence and drug abuse. As a consequence, wealthier people may artefactually appear more vulnerable to air pollution in relation with their baseline risk level since they are relatively protected from other risk factors that affect disadvantaged groups.

Policy considerations

The issue of exposure and health inequalities in relation to ambient air quality is complex and calls for a global appraisal. There is no single pattern nor, of course, single solution. However, urban planning policies that would look for 'spatial multipolarity and social diversity' might play at the very roots of these inequalities. Multipolarity refers to the structure of our large metropolitan areas. Currently, with some variation across and within countries, European cities tend to be laid out in a concentric pattern: historical and cultural areas concentrated in the centre, with also a high proportion of businesses and expensive housing, while low-cost residential areas are progressively expelled to the outskirts, where also industrial activities are located. In contrast to this concentric structure, 'multipolarity' calls for urban poles that provide a range of amenities (housing, workplaces, commercial, cultural or leisure sites) tending to reduce the need for long distance commuting in polluted environments. *Diversity* is a complementary principle of multipolarity, where each pole would provide the widest possible variety of activities and, most importantly, of housing profiles, places for the rich being intermingled with council residence. This diversity scheme would prevent the formation of peripheral clusters of poor housing, which is typically associated with lack of access to good education and other cultural amenities: the further they are from the city centres, the more likely they are to be let in a marginal status. As described above, this is how inequalities in exposure to ambient air interplay with inequalities in other environmental stressors and vulnerability factors.

Conclusion and perspectives

Few European studies investigated the effect modification of socio-economic factors on the association between air pollution and health and much is yet to be understood. However, the general pattern of the current evidence is that deprived populations, although not always more exposed, experience greater harmful air pollution effects, because of vulnerability factors. Two research directions seem particularly relevant. Comparative exposure studies that would aim to assess the relative contribution of outdoor air and of a variety of microenvironments (at home, at work, while commuting, during leisure activities) across different social categories would be very informative. These disparities may vary substantially across cities and countries. A European-wide study might help understand the core determinants of these inequalities. For such a study to be valuable, however, great efforts should be put on harmonization of methods and definitions. Further, very little data concern children. Now, poverty and deprivation in early childhood may have adverse health consequences throughout the entire life. Focused studies in children are needed to better understand mechanisms through which health inequalities could arise later in life, a call which is in line with the avenue proposed by the PINCHE project.[43]

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> ## Key points
>
> - Poor populations do not always live in areas with higher outdoor air pollution in Europe; results are country and city specific.
> - Few European studies investigated the effect modification of socio-economic factors on the relation between air pollution and health and much is yet to be understood.
> - Nevertheless, there is a general pattern: irrespective of the level of exposure to ambient air, the poor are more affected by effects associated with air pollutants.
> - Policies aimed at reducing the root causes of these inequalities could strive to foster urban multipolarity and diversity, which require long-term urban planning.

References

1 Kunst AE. Describing socioeconomic inequalities in health in European countries: an overview of recent studies. *Rev Epidemiol Sante Publique* 2007;55:3–11.

2 Dalstra JA, Kunst AE, Borrell C, et al. Socioeconomic differences in the prevalence of common chronic diseases: an overview of eight European countries. *Int J Epidemiol* 2005;34:316–26.

3 Mitchell G, Dorling D. An environmental justice analysis of British air quality. *Environ Plann A* 2003;35:909–29.

4 Passchier-Vermeer W, Passchier WF. Noise exposure and public health. *Environ Health Perspect* 2000;Suppl 1:123–31.

5 Evans GW, Kantrowitz E. Socioeconomic status and health: the potential role of environmental risk exposure. *Annu Rev Public Health* 2002;23:303–31.

6 O'Neill MS, McMichael AJ, Schwartz J, Wartenberg D. Poverty, environment, and health: the role of environmental epidemiology and environmental epidemiologists. *Epidemiology* 2007;18:664–8.

7 McLeod H, Langford I, Jones A, et al. The relationship between socio-economic indicators and air pollution in England and Wales: implications for environmental justice. *Reg Environ Change* 2000;1:18–85.

8 Brainard J, Jones A, Bateman I, et al. Modelling environmental equity: access to air quality in Birmingham, England. *Environ Plann A* 2002;34:695–716.

9 Mitchell G. Forecasting environmental equity: air quality responses to road user charging in Leeds, UK. *J Environ Manage* 2005;77:212–26.

10 Wheeler BW, Ben-Shlomo Y. Environmental equity, air quality, socioeconomic status, and respiratory health: a linkage analysis of routine data from the Health Survey for England. *J Epidemiol Community Health* 2005;59:948–54.

11 Namdeo A, Stringer C. Investigating the relationship between air pollution, health and social deprivation in Leeds, UK. *Environ Int* 2008;34:585–91.

12 Tonne C, Beevers S, Armstrong B, et al. Air pollution and motality benefits of the London congestion charge: spatial and socioeconomic inequalities. *Occup Environ Med* 2008;65:620–7.

13 Briggs D, Abellan JJ, Fecht D. Environmental inequity in England: small area associations between socio-economic status and environmental pollution. *Soc Sci Med* 2008;42:1612–29.

14 Naess O, Piro FN, Nafstad P, et al. Air pollution, social deprivation, and mortality: a multilevel cohort study. *Epidemiology* 2007;18:686–94.

15 Nafstad P, Haheim LL, Wisloff T, et al. Urban air pollution and mortality in a cohort of Norwegian men. *Environ Health Perspect* 2004;112:610–5.

16 Rotko T, Kousa A, Alm S, Jantunen M. Exposures to nitrogen dioxide in EXPOLIS-Helsinki: microenvironment, behavioral and sociodemographic factors. *J Exp Anal Environ Epidemiol* 2001;11:216–23.

17 Rotko T, Koistinen K, Hänninen O, Jantunen M. Sociodemographic descriptors of personal exposure to fine particles ($PM_{2.5}$) in EXPOLIS Helsinki. *J Exp Anal Environ Epidemiol* 2000;10:385.

18 Stroh E, Oudin A, Gustafsson S, et al. Are associations between socio-economic characteristics and exposure to air pollution a question of study area size? An example from Scania, Sweden. *Int J Health Geogr* 2005;4:30.

19 Chaix B, Gustafsson S, Jerrett M, et al. Children's exposure to nitrogen dioxide in Sweden: investigating environmental injustice in an egalitarian country. *J Epidemiol Community Health* 2006;60:234–41.

20 Kruize H, Driessen PP, Glasbergen P, van Egmond KN. Environmental equity and the role of public policy: experiences in the Rijnmond region. *Environ Manage* 2007;40:578–95.

21 Schikowski T, Sugiri D, Reimann V, et al. Contribution of smoking and air pollution exposure in urban areas to social differences in respiratory health. *BMC Public Health* 2008;8:179.

22 Forastiere F, Stafoggia M, Tasco C, et al. Socioeconomic status, particulate air pollution, and daily mortality: differential exposure or differential susceptibility. *Am J Ind Med* 2007;50:208–16.

23 Havard S, Deguen S, Bodin J, et al. A small-area index of socioeconomic deprivation to capture health inequalities in France. *Soc Sci Med* 2008;67:2007–16.

24 Havard S, Deguen S, Zmirou-Navier D, et al. Traffic-related air pollution and socioeconomic status: a spatial autocorrelation study to assess environmental equity on a small-area scale. *Epidemiology* 2009;20:223–30.

25 Wojtyniak B, Rabczenko D, Stokwiszewski J. Does air pollution has respect for socio-economic status of people (abstract). *Epidemiology* 2001;12:S64.

26 Filleul L, Rondeau V, Cantagrel A, et al. Do subject characteristics modify the effects of particulate air pollution on daily mortality among the elderly? *J Occup Environ Med* 2004;46:1115–22.

27 Filleul L, Baldi I, Dartigues JF, Tessier JF. Risk factors among elderly for short term deaths related to high levels of air pollution. *Occup Environ Med* 2003;60:684–8.

28 Havard S, Pédrono G, Schillinger C, et al. Air pollution and myocardial infarction—a small-area case crossover in Strasbourg, France, influence of individual and area characteristics. *Epidemiology* 2008;19:S197.

29 Laurent O, Pedrono G, Segala C, et al. Air pollution, asthma attacks, and socioeconomic deprivation: a small-area case-crossover study. *Am J Epidemiol* 2008;168:58–65.

30 Havard S, Deguen S, Zmirou-Navier D, et al. Traffic-related air pollution and socioeconomic status: a spatial autocorrelation study to assess environmental equity on a small-area scale. *Epidemiology* 2009;20:223–30.

31 Laurent O, Pedrono G, Filleul L, et al. Influence of socioeconomic deprivation on the relation between air pollution and beta-agonist sales for asthma. *Chest* 2009;135:717–23.

32 Charafeddine R, Boden LI. Does income inequality modify the association between air pollution and health? *Environ Res* 2008;106:81–8.

33 Zeka A, Zanobetti A, Schwartz J. Individual-level modifiers of the effects of particulate matter on daily mortality. *Am J Epidemiol* 2006;163:849–59.

34 Kan H, London SJ, Chen G, et al. Season, sex, age, and education as modifiers of the effects of outdoor air pollution on daily mortality in Shanghai, China: The Public Health and Air Pollution in Asia (PAPA) Study. *Environ Health Perspect* 2008;116:1183–8.

35 Sun R, Gu D. Air pollution, economic development of communities, and health status among the elderly in urban China. *Am J Epidemiol* 2008;168:1311–18.

36 Gouveia N, Fletcher T. Time series analysis of air pollution and mortality: effects by cause, age and socioeconomic status. *J Epidemiol Community Health* 2000;54:750–5.

37 Martins MC, Fatigati FL, Vespoli TC, et al. Influence of socioeconomic conditions on air pollution adverse health effects in elderly people: an analysis of six regions in Sao Paulo, Brazil. *J Epidemiol Community Health* 2004;58:41–6.

38 Bowen W. An analytical review of environmental justice research: what do we really know? *Environ Manage* 2002;29:3–15.

39 Haynes K, Lall S, Trice M. Spatial issues in environmental equity. *Int J Environ Tech Manag* 2001;1:17–31.

40 Been V, Gupta G. What's fairness go to do with it? Environmental justice and the siting of locally undesirable land uses. *Cornell Law Rev* 1993;78:1001–36.

41 Bell LM, Dominici F. Effect modification by community characteristics on the short-term effects of ozone exposure and mortality in 98 US communities. *Am J Epidemiol* 2008;167:986–97.

42 Romieu I, Ramirez-Aguilar M, Moreno-Macias H, et al. Infant mortality and air pollution: modifying effect by social class. *J Occup Environ Med* 2004;46:1210–6.

43 Bolte G, Kohlhuber M, Weiland SK, et al. Socioeconomic factors in EU-funded studies of children's environmental health. *Eur J Epidemiol* 2005;20:289–91.