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Socioeconomic position and outdoor nitrogen dioxide (NO_2) exposure in Western Europe: A multi-city analysis

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ABSTRACT

Background: Inconsistent associations between socioeconomic position (SEP) and outdoor air pollution have been reported in Europe, but methodological differences prevent any direct between-study comparison.
Objectives: Assess and compare the association between SEP and outdoor nitrogen dioxide (NO_2) exposure as a marker of traffic exhaust, in 16 cities from eight Western European countries.
Methods: Three SEP indicators, two defined at individual-level (education and occupation) and one at neighborhood-level (unemployment rate) were assessed in three European multicenter cohorts. NO_2 annual concentration exposure was estimated at participants' addresses with land use regression models developed within the European Study of Cohorts for Air Pollution Effects (ESCAPE; http://www.escapeproject.eu/). Pooled and city-specific linear regressions were used to analyze associations between each SEP indicator and NO_2. Heterogeneity across cities was assessed using the Higgins' I-squared test (I^2).

Abbreviations: ECRHS, European Community Respiratory Health Survey; EGEA, French Epidemiological family-based study of the Genetics and Environment of Asthma; ESCAPE, European Study of Cohorts for Air Pollution Effects; LUR, land use regression; MAUP, modifiable area unit problem; NO_2, nitrogen dioxide; OC, occupational class; PM, particulate matter; SAPALDIA, Swiss Cohort Study on Air Pollution and Lung and Heart Diseases in Adults; SEP, socioeconomic position.

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Results: The study population included 5692 participants. Pooled analysis showed that participants with lower individual-SEP were less exposed to NO_2. Conversely, participants living in neighborhoods with higher unemployment rate were more exposed. City-specific results exhibited strong heterogeneity ($I^2 > 76\%$ for the three SEP indicators) resulting in variation of the individual- and neighborhood-SEP patterns of NO_2 exposure across cities. The coefficients from a model that included both individual- and neighborhood-SEP indicators were similar to the unadjusted coefficients, suggesting independent associations.

Conclusions: Our study showed for the first time using homogenized measures of outcome and exposure across 16 cities the important heterogeneity regarding the association between SEP and NO_2 in Western Europe. Importantly, our results showed that individual- and neighborhood-SEP indicators capture different aspects of the association between SEP and exposure to air pollution, stressing the importance of considering both in air pollution health effects studies.

1. Introduction

Environmental inequality refers to a differential distribution of environmental hazards across socioeconomic or socio-demographic groups (Bolte et al., 2012). Historically, research on environmental inequality has emerged in the United States (US) following the Environmental Justice Movement (O'Neill et al., 2003; Morello-Frosch et al., 2011; Evans & Kantrowitz, 2002; Bowen, 2002). Repeatedly, US studies reported that lower socioeconomic or minority groups were more likely to be exposed to higher traffic-related air pollution exposure such as nitrogen dioxide (NO_2) or particulate matter (PM) (Hajat et al., 2015). However, results from US studies cannot be extended to European countries because of very different socio-spatial characteristics, specifically in urban areas (Musterd, 2005). For example, one of the main differences is that in general in most US cities, lower socioeconomic groups tend to live downtown when upper socioeconomic groups reside in the suburbs. In European cities, compared to US, social segregation is lower and lower socioeconomic groups rather live on the outskirts of the city (Musterd, 2005).

In Europe, a rather limited number of studies compared to US had investigated the association between socioeconomic position (SEP) and air pollution, mainly in the UK first and then in other European countries (Hajat et al., 2015; Pye et al., 2008). Inconsistent results have been reported in the European literature (Deguen & Zmirou-Navier, 2010). Some studies reported that populations with low SEP are more exposed to outdoor air pollution (Chaix et al., 2006a; Rotko et al., 2001; Schikowski et al., 2008; Wheeler & Ben-Shlomo, 2005; Brainard et al., 2002) while other studies reported an inverse association (Forastiere et al., 2007; Nafstad et al., 2004; Fernandez-Somoano & Tardon, 2014; Wheeler, 2004). Nonlinear association (higher exposure in middle class) (Havard et al., 2009) and no association (Vrijheid et al., 2012) were also reported. Inconsistent results were also reported within the same country, for instance in France or Spain (Vrijheid et al., 2012; Padilla et al., 2014; Fernández-Somoano et al., 2013; Morelli et al., 2016). However, these studies were difficult to compare with each other because they used different methodologies to assess air pollution exposure or to define SEP (Hajat et al., 2015; Miao et al., 2015). Moreover, most studies relied on ecological data that can raise methodological issues such as ecological fallacy, modifiable area unit problem (MAUP) or spatial autocorrelation (Havard et al., 2009; Jerrett & Finkelstein, 2005). Few studies used individual-level data (i.e. air pollution exposure at residential address and individual-level SEP) or multilevel data (i.e. SEP estimated at individual- and area-level) (Forastiere et al., 2007; Fernandez-Somoano & Tardon, 2014; Llop et al., 2011; Chaix et al., 2006b; Naess et al., 2007; Cesaroni et al., 2010; Goodman et al., 2011). Recent evidence showed the importance of considering SEP at both individual and area levels because they are independently associated with health outcomes (Hajat et al., 2015; Chaix et al., 2006a; Bell et al., 2005a; Stafford, 2003; Diez Roux, 2007).

More generally, the association between SEP and air pollution still needs to be investigated in Europe (Hajat et al., 2015; Miao et al., 2015) as SEP is one of the major potential determinants of variability in the association between air pollution and health (O'Neill et al., 2003; Bell et al., 2005b; Jerrett et al., 2011).

Within the framework of the multicenter European Study of Cohorts for Air Pollution Effects (ESCAPE) (Beelen et al., 2013), we had the opportunity to tackle this research gap using outdoor NO_2 annual concentrations at participants' home addresses estimated from standardized procedures across a large range of European cities (Beelen et al., 2013). The main objective of the present analysis was to test the environmental justice hypothesis that people with lower SEP (defined at both individual and neighborhood level) were more exposed to traffic related air pollution exposure than people with higher SEP in Western Europe.

2. Materials and methods

2.1. Study population

This cross-sectional study included participants of three multicenter epidemiological European cohorts that had previously collaborated together (Boudier et al., 2013) and were involved in the ESCAPE study: the French Epidemiological family-based study of the Genetics and Environment of Asthma (EGEA2) (2003–2007) (Siroux et al., 2009), and two population-based studies: the European Community Respiratory Health Survey (ECRHSII) (1999–2002) (Jarvis, 2002) and The Swiss Cohort Study on Air Pollution and Lung and Heart Diseases in Adults (SAPALDIA2) (2001 − 2003) (Ackermann-Liebrich et al., 2005). Details on each cohort are given elsewhere (Siroux et al., 2009; Jarvis, 2002; Ackermann-Liebrich et al., 2005) and summarized in the supplementary materials. For the three cohorts, information on participants were collected from detailed, standardized and validated questionnaires completed by face-to-face interviews.

Initially, the ESCAPE study included a subsample of the three cohorts ($n = 9556$ participants, Fig. 1) from 20 urban areas of eight Western European countries. Of these 20 areas, we were able to recover homogenized SEP data at individual and neighborhood level for 16 ($n = 5692$ participants: 4002, 1078 and 612 in ECRHS, EGEA and SAPALDIA respectively; Fig. 1) including Norwich, Ipswich (Great Britain; GB); Antwerp (Belgium; BE); Paris, Lyon, Grenoble, Marseille (France; FR); Geneva, (Switzerland; CH); Verona, Pavia, Turin (Italy; IT); Oviedo, Galdakao, Barcelona, Albacete, Huelva (Spain; SP) (Fig. S1). The areas covered by ESCAPE were of substantially different sizes (Table S1) with a range of density population from 152 to 21,154 inhabitants/km^2 (Cyrys et al., 2012). Most of them could be defined as metropolitan areas (large cities with surrounding smaller suburban communities) but some areas were restricted to a single city (municipality). For purposes of clarity, we refer to these different areas as “cities”.

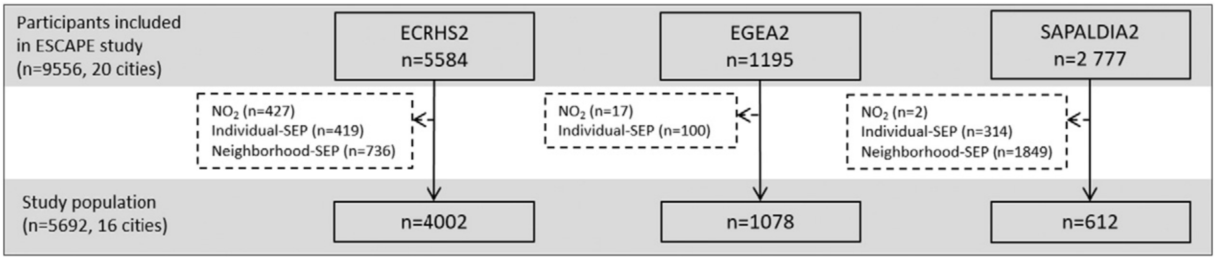

Fig. 1. Flow chart of the study population. Dotted frame: missing data. ESCAPE: European Study of Cohorts for Air Pollution Effects. ECRHS: European Community Respiratory Health Survey (1999–2002). EGEA: Epidemiological study on Genetics and Environment of Asthma (2003–2007). SAPALDIA: Swiss Cohort Study on Air Pollution and Lung and Heart Diseases in Adults (2001–2003).

2.2. NO_2 exposure assessment

We considered nitrogen dioxide (NO_2) as a marker of near-road traffic-related air pollution (WHO Regional Office for Europe, 2005). The major sources of NO_2 are motorized road traffic, industry, shipping and heating (Cyrys et al., 2012). In the framework of ESCAPE, a single harmonized exposure assessment protocol has been developed to estimate the NO_2 annual concentrations. A common protocol described in detail in Beelen et al. was used to ensure high standardization of all procedures (i.e. measurement and estimation model) across the study areas (Beelen et al., 2013). Briefly, in each city covered, two-week integrated NO_2 measurements at approximately 40 urban sites were made in three different seasons over a one-year period between 2008 and 2011. City-specific land use regression (LUR) models (see Supplementary materials) were developed to explain the spatial variation of NO_2 using a variety of geographical data including traffic, population and land use variables. The model explained variances (R^2) of the LUR models ranged from 55% in Huelva to 92% in Pavia, 10 out of the 16 cities have a R^2 above 75% (Beelen et al., 2013). These LUR models were used to assign estimates of NO_2 annual average concentrations at each participant's geocoded residential address. Back-extrapolated estimates were also derived because ESCAPE measurement campaigns took place after the health surveys for the three cohorts (Beelen et al., 2014). Correlations between back-extrapolated and non-back-extrapolated concentrations were high (Pearson correlation coefficient = 0.95) so we only considered the non-back-extrapolated data in the present analysis.

2.3. Markers of socioeconomic position

We indexed SEP defined at two different levels.

2.3.1. Individual-level SEP

We characterized individual-level SEP based on educational level and occupational class. For the three cohorts, educational level corresponded to the age at completion of full-time education. We categorized the continuous educational variable into country-specific tertiles (high, medium and low). Occupational class was based on the longest job held between baseline and follow-up (in average 10–12 years), and categorized in five classes according to the International Standard Classification of Occupation (ISCO-1988) (International Standard Classification of Occupations, 1991): Manager and Professional (Occupational Class-I); Technician & associate (OC-II); Other non-manual (OC-III); Skilled, semi-skilled and unskilled manual (OC-IV) and "not in labor force".

2.3.2. Neighborhood-level SEP

To characterize the socioeconomic residential environment of the participants, we used the neighborhood unemployment rate (i.e. proportion of unemployed persons of the labor force). The neighborhood level corresponded to the smallest geographical level unit (with a population size ranging from 169 to 2000 inhabitants) with census-based data available in the different countries (see Table S2 for neighborhood specific characteristics). We obtained the unemployment rate variable from 2001 national censuses (except for France: 2008 and Switzerland: 2006). As the magnitude of the unemployment rate varied across European countries, we standardized it using country-specific z-scores to take this variability into account.

2.4. Strategy of analysis

2.4.1. Main analyses

The strategy of analysis aimed to test the hypothesis that the NO_2 annual concentration (dependent variable) differs according to the individual- and neighborhood-SEP of the participants (explanatory variables).

We performed analyses considering first the pooled dataset and then each city separately, due to the heterogeneity of the associations between SEP and air pollution among the cities (assessed with the Higgins' I-squared test (I^2) (Higgins et al., 2003)) We ran several multilevel linear regression models (Table S3) with neighborhood random effects (plus city random effects for the pooled dataset) including one individual SEP indicator (education or occupation) mutually adjusted for neighborhood unemployment rate. In the supplementary materials, we present the results for the single-level linear regression models that ignore the nested structure of the observations.

We transformed NO_2 using a natural log transformation to obtain a normally distributed variable. For ease of interpretation, we converted the regression coefficients (βs) into percent change (and 95% Confidence Interval (CI)) per one unit increase in the explanatory factor using the formula $[\exp(\beta) - 1] * 100$ (a 95% CI which does not include zero indicates the presence of significant differences). The considered unit for unemployment rate was 1 standard deviation (SD). For the individual-level SEP variables, we considered each subgroup and tested the statistical differences of the coefficients against the highest group (thus reference group were high educational level and OC-I for occupational class). We deliberately did not show results for participants who were not in the labor force as this class was too heterogeneous to draw any kind of conclusion (i.e. housepersons, unemployed, not working because of poor health, full-time student and retired). This category was excluded to assess the trend across the occupational groups.

2.4.2. Additional analyses

We ran a sensitivity analysis using logistic regression models considering high vs. low exposure (high exposure was defined as an exposure above the 75th percentile of the distribution for each city). All models were adjusted for cohort, age and sex. We checked for potential interactions between SEP and sex, SEP and age and between individual- and neighborhood-level SEP (Supplementary materials). Analyses were conducted using R statistical software (Version 3.0.3) and SAS 9.3.

As pointed out above some "cities" included in this analysis had a wide geographic coverage. For example, the city labelled "Paris" (FR) covered actually the metropolitan area of Paris-Region (i.e. 12,000 km^2). Therefore, we ran a sensitivity analysis by examining more in detail this area: instead of considering participants of Paris in only one area, we considered three distinctive areas (i.e. City of Paris, the inner-suburbs and the outer-suburbs) defined by particular sociodemographic and geographic situations that could influence the association between SEP and air pollution. The methods and results are presented in detail in the Supplementary materials and discussed in the main article.

3. Results

3.1. Study population characteristics

The study population (Table 1a) was composed of 48% males, with a mean age (±standard deviation; ±SD) of 44 (±11) years. Regarding the NO_2 distribution, we found substantial variability between cities with a mean ranging from 21 (±5) (Pavia; IT) to 57 (±14) μg m^{-3} (Barcelona; ES). Substantial variability was also found within cities. The average range for NO_2 (difference between the highest and the lowest annual average) within each area was 50.3 μg m^{-3}. The largest variation for NO_2 was found in the two largest cities Paris (FR) (85.0) and Barcelona (SP) (92.8).

Regarding the socioeconomic characteristics of the population (Table 1b), participants completed their education on average at age 20 (±4) years. The proportion of manual workers ranged from 6% (Paris; FR) to 38% (Galdakao; SP) and was generally higher in the Spanish cities. On average, participants with lower educational attainment were employed in less skilled occupations (p-value for trend < 0.001) (Table S4). The neighborhood unemployment rate varied from 3% (Pavia; IT) to 22% (Huelva; SP). Participants with lower educational attainment or less skilled occupations were more likely to live in neighborhoods with higher unemployment rate. However, the associations did not reach the level of significance in 7 and 6 out of the 16 cities for education and occupation respectively (Tables S5a—S5b).

3.2. Pooled results

Pooled results are shown in Table 2. In the model taking into account only clustering within cities, low educational level and manual occupations were associated with a lower NO_2 exposure (Percent difference (95% CI) Low vs. high educational level = −6.9% (−9.1; −4.7); OC-IV vs. OC-I = −5.6% (−8.2; −3.0)). Conversely, higher neighborhood unemployment rate was associated with higher NO_2 exposure (7.3% (6.2; 8.5) per 1 SD increase in the unemployment rate). The introduction of individual- and neighborhood-SEP in the same model did not substantially alter effect estimates (Low vs. High educational level = −8.7% (−10.8; −6.5) and 7.8% (6.7; 8.9) per 1 SD increase in the unemployment rate). Accounting for both city and neighborhood clustering decreased the effect size of both the individual- and neighborhood-SEP. Associations remained significant for educational level and the unemployment rate.

3.3. City-specific results

In the city-specific analyses using standard linear regression models (Table S4), associations with NO_2 were highly heterogeneous for all SEP indicators ($I^2 > 76\%$, $p < 0.001$). Using multilevel linear regression models, individual-SEP was weakly or not associated with NO_2 exposure for most cities (14 out of 16 cities). For educational level (Table 3a), significant associations were only found in Lyon (FR) (Low vs. High = −3.6 (−12.3; −5.9)) and Verona (IT) (−16.1 (−26.5; −4.3)). For occupational class (Table 3b), significant associations were found for the middle class in Paris (FR) (OC-III vs. OC-I = −3.3 (−6.4; −0.1)) and Oviedo (−8.7 (−15.7; −1.2)). Living in a neighborhood with higher unemployment rate was associated with higher NO_2 exposure (regardless of the individual-SEP marker included in the model) in 11 out of 16 cities. In Oviedo (ES) and Barcelona (ES) an inverse association was observed.

3.4. Additional analyses

Results from the logistic regression models (high vs. low exposure) were consistent with the linear regression ones for the educational level (Table S6a) as well for occupational class (Table S6b).

In Paris-Region (FR), when considering participants in three distinctive areas (i.e. city of Paris, inner suburbs and outer suburbs; supplementary materials), participants with lower educational level or occupational class were less exposed to air pollution (not significant) but those living in neighborhood with higher unemployment rate were more exposed. These results are consistent with those observed when considering participants in one area.

4. Discussion

We investigated, in three European cohorts, whether SEP evaluated at both individual- and neighborhood-level was associated with traffic related air pollution exposure across sixteen Western European cities. The pooled analyses masked important heterogeneity across the cities showing that city appeared to be the major predictor of the association between SEP and NO_2 exposure.

The associations between individual-SEP and NO_2 were generally weak and inconsistent across the cities. This is in accordance with those of the three studies that used a comparable approach to ours (Fernandez-Somoano & Tardon, 2014; Vrijheid et al., 2012; Hajat et al., 2013). Education and occupation showed the same pattern with NO_2 in the pooled data and in most cities, in the city specific analyses, showing that both indicators measured the same concept (Galobardes, 2001; Stronks et al., 1997). The associations between neighborhood-SEP and NO_2 were in the opposite direction (higher exposure in lower neighborhood-SEP) compared to the individual-SEP variables, both in the pooled data and in most cities in the city-specific models. This has also been observed in other studies in Europe (Goodman et al., 2011) and in Montreal, Canada (Crouse et al., 2009).

One possible explanation for the difference in direction is that the neighborhood-SEP is capturing aspects beyond the SEP of the population living in that area, such as how industrialized the neighborhood may be. Moreover, NO_2 variability was relatively small across the individual-SEP groups, and after adjusting for neighborhood-SEP there was little evidence of potential confounding by individual-SEP. Place of residence is strongly patterned by social position and outdoor air

Table 1a
Characteristics of the population (by city and data pooled).

City	Country	n	Sex	Age	NO_2 ($\mu g * m^{-3}$)	
			Men, %	Mean ± SD	Mean ± SD	Q1–Q3
Norwich[a]	UK	242	43.0	43.6 ± 6.5	25.6 ± 5.7	22.8–28.7
Ipswich[a]	UK	338	42.3	42.4 ± 6.8	24.2 ± 4.0	22.7–26.0
Antwerp[a]	Belgium	500	49.9	42.7 ± 6.9	39.4 ± 9.0	32.7–45.6
Paris[a,b]	France	785	48.3	41.7 ± 12.9	36.4 ± 13.4	27.4–42.6
Lyon[a]	France	210	46.7	48.4 ± 15.3	28.7 ± 13.5	16.9–40.6
Grenoble[a,b]	France	690	52.9	44.9 ± 13.4	27.5 ± 8.2	20.8–32.9
Marseille[b]	France	119	43.7	49.2 ± 15.8	26.1 ± 8.2	21.4–31.1
Geneva[c]	Switzerland	612	49.4	52.1 ± 11.3	26.5 ± 7.0	21.1–31.3
Verona[a]	Italy	179	44.1	42.6 ± 7.1	30.7 ± 13.8	22.6–40.2
Pavia[a]	Italy	188	53.7	44.2 ± 6.6	20.5 ± 4.8	17.6–21.8
Turin[a]	Italy	170	46.6	42.9 ± 7.0	54.9 ± 10.1	49.2–61.9
Oviedo[a]	Spain	315	49.8	42.9 ± 7.1	36.6 ± 12.5	29.3–43.9
Galdakao[a]	Spain	408	48.5	40.7 ± 7.3	23.9 ± 6.6	18.6–28.3
Barcelona[a]	Spain	284	44.4	41.9 ± 7.1	57.4 ± 14.1	49.6–62.4
Albacete[a]	Spain	419	46.8	40.8 ± 7.3	28.6 ± 14.8	19.5–38.1
Huelva[a]	Spain	233	50.2	41.1 ± 7.2	25.2 ± 6.4	20.6–29.8
Pooled data		5692	48.2	43.9 ± 10.6	31.8 ± 13.6	22.4–38.6

Cities are sorted from north to south.
Participants were from [a]ECRHS, [b]EGEA, [c]SAPALDIA; Paris: ECRHS $n = 386$, EGEA $n = 399$, Grenoble: ECRHS $n = 350$, EGEA $n = 340$.

Table 1b
Socioeconomic characteristics of the population (by city and data pooled).

City	*n*	Individual-level SEP						Neighborhood-level SEP
		Age at end of school	Occupational class, %					Unemployment rate*
		Mean ± SD	Managers and professionals (OC-I)	Technicians & associate professionals (OC-II)	Other non-manuals (OC-III)	Manuals (OC-IV)	*Not in labor force*	Mean ± SD (min-max)
Norwich[a]	242	17.6 ± 3.1	25.6	19.4	27.3	24.0	*3.7*	11.1 ± 7.2 (2.1–34.1)
Ipswich[a]	338	17.1 ± 2.6	22.5	16.6	30.8	22.2	*8.0*	10.4 ± 6.6 (2.4–32.0)
Antwerp[a]	500	20.2 ± 3.1	33.0	18.6	31.0	16.8	*0.7*	8.2 ± 5.9 (0.8–31.2)
Paris[a,b]	785	21.3 ± 3.6	41.7	23.6	18.5	6.2	*10.1*	10.6 ± 4.0 (3.0–28.0)
Lyon[a]	210	19.5 ± 3.7	20.5	24.8	26.2	21.0	*7.6*	9.1 ± 3.8 (3.4–25.1)
Grenoble[a,b]	690	20.8 ± 3.8	37.5	20.1	17.4	13.9	*11.0*	9.8 ± 4.5 (3.4–31.3)
Marseille[b]	119	20.6 ± 3.4	46.2	20.2	14.3	9.3	*10.1*	12.1 ± 5.5 (4.9–35.0)
Geneva[c]	612	20.5 ± 4.3	32.4	20.4	24.8	11.4	*11.0*	4.3 ± 1.4 (0.7–9.1)
Verona[a]	179	19.0 ± 4.7	25.8	13.7	29.0	23.7	*7.9*	4.5 ± 3.0 (1.0–15.4)
Pavia[a]	188	18.7 ± 4.6	25.8	13.7	29.0	23.7	*7.9*	3.4 ± 2.5 (0.7–14.3)
Turin[a]	170	19.5 ± 5.2	21.6	13.1	36.4	22.1	*6.8*	7.4 ± 4.1 (1.4–21.7)
Oviedo[a]	315	19.3 ± 4.6	26.7	10.8	29.2	28.6	*4.8*	14.0 ± 3.0 (7.5–33.3)
Galdakao[a]	408	18.2 ± 4.1	17.9	8.6	25.3	37.7	*10.5*	10.7 ± 3.5 (3.1–21.9)
Barcelona[a]	284	18.8 ± 4.9	28.9	14.4	29.6	21.1	*6.0*	10.9 ± 3.3 (4.1–26.4)
Albacete[a]	419	17.7 ± 4.9	17.0	10.0	29.4	33.2	*10.5*	14.6 ± 5.3 (7.7–60.4)
Huelva[a]	233	18.0 ± 4.6	17.6	9.4	27.9	30.5	*14.6*	21.8 ± 6.7 (10.7–41.4)
Pooled data	5692	19.5 ± 4.3	29.1	17.0	25.6	19.6	*8.7*	10.0 ± 6.0 (0.7–60.4)

Cities are sorted from north to south.
SD = standard deviation.
Participants were from [a]ECRHS, [b]EGEA, [c]SAPALDIA; Paris: ECRHS *n* = 386, EGEA *n* = 399, Grenoble: ECRHS *n* = 350, EGEA *n* = 340.
OC = occupational class. Not in labor force participants (in italics) included unemployed, retired, housepersons and students.
* The neighborhood unemployment rate has been assigned individually to participants using their residential addresses.

pollution is spatially located within cities, therefore the degree to which air pollution is socially patterned is likely to occur more at area-level as well (Diez Roux, 2007).

Accounting for both city and neighborhood clustering using a two level random intercept model drastically decreased the size effects of the associations for both individual- and area-SEP markers compared to the single level linear regression model (Table S7). This has been observed in other studies (Goodman et al., 2011; Jerrett et al., 2011; Havard et al., 2008) showing the importance to accounting for clustering in analyses including spatially nested data. With the multilevel approach the effect of unemployment rate remained in all cities but the effect of the individual-SEP decreased and even became null for several cities showing that variability was mainly explained by the city first then by the neighborhoods and for a smaller part by the individual-SEP. We looked at some socioeconomic variables at city level (e.g. population density, gross domestic product, etc.) to try to explain the heterogeneity of the association between SEP and NO_2 among the cities using a meta-regression. However, none of the tested variables explained this heterogeneity (not shown).

To the best of our knowledge this is the first study including a large sample of cities geographically representative of Western Europe, with important within- and between-area variability of air pollution

Table 2
Pooled results for the association between NO_2 concentration ($\mu g * m^{-3}$) and SEP markers ($n = 5692$) in percent change (95%CI).

		n	Multilevel model with city at level[a]			Multilevel model with neighborhood (level 2) and city (level 3)[b]		
			Adjusted for individual factors	Mutually adjusted for individual and neighborhood SEP		Adjusted for individual factors	Mutually adjusted for individual and neighborhood SEP	
Individual-level SEP								
Educational level	High (ref)	1917	–	–		–	–	
	Medium	2001	–4.5 (−6.6; −2.3)	–5.1 (−7.1; −3.0)		–1.3 (−2.7; −0.2)	–1.3 (−2.7; 0.2)	
	Low	1774	–6.9 (−9.1; −4.7)	–8.7 (−10.8; −6.5)		–1.7 (−3.2; −0.1)	–1.8 (−3.3; −0.2)	
p-value for trend			<0.0001	<0.0001		0.04	0.03	
Occupational class	OC-I (ref)	1657	–		–	–		–
	OC-II	967	–2.6 (−5.3; 0.2)		–2.7 (−5.4;0.01)	1.0 (−0.8; 2.9)		1.0 (−0.8; 2.9)
	OC-III	1457	–1.0 (−3.5; 1.6)		–2.0 (−4.1; 0.5)	–0.6 (−2.3;1.0)		–0.7 (−2.3; 1.0)
	OC-IV	1118	–5.6 (−8.2; −3.0)		–7.9 (−10.4; −5.3)	–0.6 (−2.5;1.2)		–0.8 (−2.6; 1.1)
p-value for trend			0.001		<0.0001	0.03		0.03
Neighborhood-level SEP								
Unemployment rate		5692	7.3 (6.2; 8.5)	7.8 (6.7; 8.9)[c]	7.7 (6.6; 8.8)[d]	3.33 (0.71; 6.01)	3.2 (1.5; 5.0)[c]	3.3 (1.5; 5.1)[d]

All models are adjusted for cohort, age and sex.
Results are expressed in percent change in NO_2 ($\mu g * m^{-3}$) concentration adjusted for cohort, age, sex. Negative value means a decrease in NO_2 (in percent) compared to the reference class for categorical variable and for 1 SD increase for the continuous variable; *p*-value for trend were calculated by introducing the categorical variables in continuous. The unemployment rate has been transformed in z-score, the change in NO_2 is showed for 1 standard deviation.
Occupational class (OC): OC-I: managers and professionals, OC-II: technician and associate professionals, OC-III: other non-manuals, OC-IV: skilled, semi-skilled and unskilled manuals.
[a] A multilevel model was performed with city at level-2 (random intercept for city level).
[b] A multilevel model was performed with neighborhood at level-2 and city at level-3 (random intercept for city and neighborhood levels).
[c] Mutually adjusted for educational level and neighborhood unemployment rate.
[d] Mutually adjusted for occupational class and neighborhood unemployment rate.

Table 3a
Percent change (95%CI) in NO_2 concentration ($\mu g * m^{-3}$) in association to educational level mutually adjusted for neighborhood unemployment rate ($n = 5692$).

City	n	Educational level (ref = high)			Neighborhood unemployment rate
		Medium	Low	p-value for trend	
Norwich	242	−0.9 (−5.7; 4.3)	−1.1 (−7.7; 6.0)	0.71	9.4 (5.1; 13.8)
Ipswich	338	2.0 (−0.6; 4.7)	0.5 (−2.8; 3.8)	0.69	4.9 (1.0; 8.9)
Antwerp	500	0.6 (−2.2; 3.4)	1.2 (−1.9; 4.3)	0.45	14.9 (11.8; 18.2)
Paris	785	0.1 (−2.6; 2.9)	−0.3 (−3.1; 2.6)	0.84	13.7 (9.7; 17.8)
Lyon	210	−9.4 (−17.0; −0.9)	−3.6 (−12.3; −5.9)	0.58	12.6 (2.2; 24.0)
Grenoble	690	0.5 (−2.1; 3.0)	0.8 (−1.9; 3.7)	0.56	9.3 (5.1; 13.7)
Marseille	119	−1.9 (−10.4; 7.3)	−7.1 (−16.1; 2.9)	0.13	12.1 (7.1; 17.4)
Geneva	612	−2.0 (−4.5; 0.6)	−1.8 (−4.4; 0.9)	0.18	9.5 (4.7; 14.6)
Verona	179	−0.9 (−15.8; 16.8)	−16.1 (−26.5; −4.3)	0.01	14.0 (3.6; 25.3)
Pavia	188	0.1 (−4.2; 4.6)	−1.4 (−5.4; 2.6)	0.48	2.6 (−1.0; 6.4)
Turin	170	2.8 (−5.9; 12.3)	5.9 (−3.9; 16.6)	0.22	2.3 (−1.4; 6.1)
Oviedo	315	−0.4 (−7.2; 7.0)	−5.0 (−12.3; 3.0)	0.25	−14.1 (−23.6; −3.3)
Galdakao	408	−1.3 (−5.1; 2.8)	−3.3 (−7.8; 1.5)	0.18	21.8 (14.1; 30.1)
Barcelona	284	3.3 (−2.7; 9.7)	3.7 (−3.3; 11.2)	0.28	−7.7 (−12.7; −2.4)
Albacete	419	−10.3 (−21.1; 1.9)	−8.4 (−18.4; 2.9)	0.11	−7.9 (−17.5; 2.9)
Huelva	233	−1.0 (−6.1; 4.3)	−2.6 (−8.5; 3.6)	0.39	1.9 (−2.3; 6.4)

Cities are sorted from north to south.
A multilevel linear regression model (PROC MIXED) was performed with neighborhood at level-2 (random intercept for neighborhood level); adjusted for cohort, age and sex.
Results are expressed in percent change in NO_2 ($\mu g * m^{-3}$) concentration. Negative value means a decrease in NO_2 (in percent) compared to the reference class for the categorical variable; p-value for trend were calculated by introducing the categorical variables in continuous. The unemployment rate has been transformed in z-score, the change in NO_2 is showed for 1 standard deviation.

exposure. We used NO_2 as a traffic-related pollutant known to have a great intra-urban variability and thus was the most appropriate to study socioeconomic differences at individual-level (Chaix et al., 2006a; Cyrys et al., 2012; Jerrett et al., 2005). The NO_2 annual concentrations have been estimated at participant's residential address with a single harmonized exposure assessment protocol across the cities. The measurement time of NO_2 does not overlap with the questionnaire data from the cohorts. However, we assume that spatial contrasts in outdoor NO_2 pollution were stable over time; an assumption supported from observations in different settings in European countries (Eeftens et al., 2011; Beevers et al., 2012). We used homogenized SEP indicators at both individual- and neighborhood-level. Recent evidence showed the importance of accounting SEP at both levels because they were independently associated with health outcomes (Stafford, 2003; Diez Roux, 2007; Bell et al., 2005b; Hajat et al., 2013; Chaix et al., 2010; Krieger et al., 2014) but this had rarely been investigated with air pollution exposure (Chaix et al., 2006a; Naess et al., 2007; Cesaroni et al., 2010). We used an area-based indicator defined at the smallest geographical unit available in each country to avoid MAUP as recommended (Crouse et al., 2009; Diez Roux, 2005; Maantay, 2002; Mujahid et al., 2007).

Our study has some limitations. Due to data confidentiality, we did not have access to participants' geographical coordinates for the present analysis and we were not able to analyze their spatial distribution. We applied an aspatial multilevel model to take into account the clustering of the participants within neighborhoods (Hajat et al., 2013; Havard et al., 2011) but the proportion of neighborhoods containing only one participant was relatively high in some cities (Bell et al., 2010). This highlights a common problem in studies that were not originally designed to study area-level determinants. We compared a large number of European cities, but the sample in some cities was quite small and could explain the absence of associations and large confidence intervals. The

Table 3b
Percent change (95%CI) in NO_2 concentration ($\mu g * m^{-3}$) in association to occupational class mutually adjusted for neighborhood unemployment rate ($n = 5692$).

City	n	Occupational class (ref = OC-I)				Neighborhood unemployment rate
		OC-II	OC-III	OC-IV	p-value for trend	
Norwich	242	−0.1 (−6.1; 6.2)	0.1 (−6.1; 6.7)	4.9 (−1.5; 11.8)	0.45	9.7 (5.3; 14.3)
Ipswich	338	2.3 (−1.2; 5.8)	1.6 (−1.4; 4.7)	0.6 (−2.5; 3.7)	0.99	5.0 (1.2; 9.1)
Antwerp	500	0.9 (−2.5; 4.4)	1.6 (−1.4; 4.6)	−1.7 (−5.0; 1.7)	0.63	15.1 (11. 9; 8.3)
Paris	785	−2.3 (−5.0; 0.6)	−3.3 (−6.4; −0.01)	−4.8 (−9.5; 0.1)	0.03	13.7 (9.7; 17.8)
Lyon	210	3.2 (−5.7; 12.9)	−3.9 (−12.5; 5.5)	−2.1 (−11.7; 8.6)	0.78	13.0 (2.5; 24.6)
Grenoble	690	1.8 (−1.1; 4.8)	1.1 (−2.1; 4.3)	3.1 (−0.4; 6.7)	0.20	9.1 (4.9; 13.5)
Marseille	119	−8.6 (−16.6; 0.1)	−6.9 (−15.2; 2.2)	−4.8 (−15.8; 7.7)	0.07	12.1 (7.0; 17.3)
Geneva	612	1.7 (−1.3; 4.8)	−1.0 (−3.7; 1.9)	−0.7 (−4.1; 2.8)	0.72	9.3 (4.4; 14.3)
Verona	179	1.9 (−20.8; 31.0)	−2.7 (−18.3; 15.8)	−12.9 (−28.1; 5.4)	0.07	13.3 (2.9;4.7)
Pavia	188	−2.6 (−8.2; 3.4)	−3.7 (−7.8; 0.7)	−2.5 (−7.6; 2.8)	0.17	2.7 (−0.9; 6.4)
Turin	170	9.5 (−3.6; 24.4)	9.6 (−0.6; 20.8)	11.7 (−0.1; 25.0)	0.07	2.3 (−1.3; 6.1)
Oviedo	315	0.8 (−9.5; 12.3)	−8.7 (−15.7; −1.2)	−5.9 (−13.2; 2.1)	0.07	−13.7 (−23.6; −2.8)
Galdakao	408	3.9 (−3.1; 11.4)	3.6 (−1.6; 9.0)	3.3 (−1.8; 8.6)	0.67	21.4 (13.6; 29.6)
Barcelona	284	3.4 (−4.8; 12.2)	3.4 (−2.8; 10.1)	4.1 (−2.6; 11.2)	0.16	−7.7 (−12.7; −2.5)
Albacete	419	−3.7 (−18.2; 13.5)	−6.1 (−18.2; 7.8)	−4.6 (−16.5; 9.1)	0.34	−8.3 (−18.0; 2.6)
Huelva	233	8.5 (−0.1; 17.9)	4.1 (−2.1; 10.8)	6.8 (0.1; 13.8)	0.15	1.0 (−3.2; 5.3)

Cities are sorted from north to south.
A multilevel linear regression model (PROC MIXED) was performed with neighborhood at level-2 (random intercept for neighborhood level); adjusted for cohort, age and sex. Results are expressed in percent change in NO_2 ($\mu g * m^{-3}$) concentration. Negative value means a decrease in NO_2 (in percent) compared to the reference class for the categorical variable; p-value for trend were calculated by introducing the categorical variables in continuous. The unemployment rate has been transformed in z-score, the change in NO_2 is showed for 1 standard deviation.
Occupational class (OC): OC-I: managers and professionals (ref), OC-II: technicians and associate professionals, OC-III: other non-manuals, OC-IV: skilled, semi-skilled and unskilled manuals. p-value for trend were calculated by introducing the categorical variables in continuous.

different areas were also of different sizes and with different population density. However, the additional analysis performed for the Paris-Region suggested that the results were not sensitive to this aspect.

We considered the unemployment rate, the sole indicator of neighborhood SEP uniformly available for most of the cities with ESCAPE NO_2 estimates. This single indicator does not fully describe participants' neighborhood-SEP (Diez Roux, 2007) but has been used in other studies that compared different countries regarding air pollution (Samoli et al., 2008) and has been associated with adverse health outcomes at neighborhood level (Samoli et al., 2008; van Lenthe et al., 2005; Bosma et al., 2001; Payne et al., 1993). We performed additional analyses with country-specific deprivation indices that were available at neighborhood level but only for 12 out of the 16 cities (Pornet et al., 2012; Carstairs & Morris, 1989; Alguacil Gómez et al., 2013; Caranci et al., 2010) and we found consistent results compared to the ones with the neighborhood unemployment rate (Table S8).

Finally, we did not have information on other type of exposures such as occupational and indoor exposures or time-activity patterns (Schweizer et al., 2007) which could contribute to create or reinforce environmental inequalities.

5. Conclusions

Unequal distribution to air pollution exposure according to SEP groups is complex in European cities and no general pattern exists across cities, but rather inequalities need to be specifically assessed in each city. Importantly, our results highlighted the importance of taking into account both individual- and neighborhood-SEP in order to fully describe and understand the complexity of current patterns of social inequalities relating to air pollution.

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Competing financial interest

The authors declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.envint.2016.12.026.

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