**Are air quality perception and PM2.5 exposure differently associated with cardiovascular and respiratory disease mortality in Brussels? Findings from a census-based study**

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**Abstract:**

**Background**: There is ample evidence that air pollution increases mortality risk, but most studies are based on modelled estimates of air pollution, while the subjective perception of air quality is scarcely assessed. We aimed to compare the effects of objective and subjective exposure to air pollution on cardiorespiratory mortality in Brussels, Belgium.

**Methods**: Data consisted of the 2001 Belgian census linked to registry-based mortality data for the follow-up period 2001-2014. We included individuals aged >30 years of age residing in Brussels at baseline (2001). Air pollution exposure was assessed with objective (modelled annual mean concentrations of PM2.5 in micrograms per cubic metre, µg/m3) and subjective indicators (poor self-reported air quality perception in the census). We used Cox Proportional Hazard models with age as the underlying time scale to evaluate associations with cardiovascular disease (CVD) and respiratory disease mortality, and separately, ischaemic heart disease (IHD), cerebrovascular disease, and COPD excluding asthma mortality. We specified single- and two-exposure models and evaluated effect modification by neighbourhood unemployment rate.

**Results**: 437,340 individuals were included at baseline. During follow-up (2001-2014), 22,821 (5%) individuals had died from CVDs and 8,572 (2%) from respiratory diseases. In single-exposure models, PM2.5 was significantly associated with an increased risk in CVD and IHD mortality (e.g. for IHD, per 5 µg/m3 increase: Hazard Ratio, HR:1.22, 95%CI:1.08-1.37), and poor air quality perception with COPD excluding asthma mortality (HR:1.23, 95%CI:1.15-1.33). Associations remained significant in the two-exposure models, and additionally, perception was associated with respiratory disease mortality. Associations became gradually stronger with increasing neighbourhood unemployment rate [e.g. in the highest, Q3: PM2.5 and cerebrovascular disease mortality (HR:1.53, 95%CI:1.04-2.24)].

**Conclusion**: Our findings suggest that objective and subjective exposure to air pollution increased the risk of dying from cardiovascular and respiratory diseases respectively in Brussels. These results encourage policies reducing pollution load in Brussels whilst considering socio-economic inequalities.

**Keywords:** Ambient air pollution; air quality perception; particulate matter; mortality; cardiovascular disease; respiratory disease

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**Ethics approval**

Ethics approval was not needed, all data used was anonymised and data linkages were done by a third party in Statistics Belgium to comply with privacy regulations.

**1. Introduction**

Air pollution is a complex mixture of gaseous and physical components, including fine particulate matter (PM2.5). There is currently vast evidence of a link between exposure to PM2.5 and cardiovascular and respiratory disease morbidity (Andersen et al., 2011; Gan et al., 2013; Pranata et al., 2020), and mortality (Beelen et al., 2009, 2014; Chen & Hoek, 2020; Hoek et al., 2013; Hvidtfeldt et al., 2019). Most studies assessed exposure to air pollution using objectively modelled estimates of air pollutant concentrations, and fewer studies have focussed on the effect of subjective air pollution perception on health outcomes (K. Orru et al., 2018; Pitchika et al., 2017).

Poor air quality perception could be indirectly associated with health outcomes through the activation of emotional responses after cognitive processing of the air quality, similar to the suggested indirect mechanism linking noise annoyance and health (Münzel et al., 2017). People who perceive poor air quality may be disturbed by various visual and olfactory triggers, for example smoke, gases, and odours (Bickerstaff, 2004; Claeson et al., 2013; Oglesby et al., 2000; Stenlund et al., 2009). Additionally, the health risk perception of air pollution can induce annoyance, which may exacerbate the harmful effects of ambient air pollution by activating stress-induced pathways and systemic inflammation (Golbidi et al., 2015; K. Orru et al., 2018). Thus, an interaction between objectively measured exposure to air pollution and subjective air quality perception may be at play in associations with health. As far as we are aware, no studies have investigated the link between poor perception of air quality and cardiorespiratory mortality.

Also, socioeconomic inequalities in air pollution exposure and susceptibility, known as environmental injustice, (re)produce health inequalities (Hajat et al., 2015). This has been well reported in studies on modelled air pollution estimates. However, there is some controversy regarding how social factors may affect individuals’ perception to air quality, and whether this contributes to health inequalities independently from objective air pollution exposure (Jacquemin et al., 2007; Kim et al., 2012; Klæboe et al., 2000; Oglesby et al., 2000).

The Brussels Capital Region (BCR) is the only capital in Europe where residents report overall worse quality of life compared to elsewhere in the country, which may partly be explained by the higher levels of air pollution (Leončikas & Rende, 2020). In the past, the BCR has prioritized car accessibility, worsening air quality due to highways and large amounts of traffic in the city (da Schio et al., 2019; Fierens et al., 2011; Vanhellemont, 2016). Despite efforts to improve air quality within the BCR, these structural elements still contribute to high air pollution levels (Fierens et al., 2011). Also, the BCR has a very specific socio-demographic composition compared to Belgium as a whole; a stark difference exists between poorer and wealthier neighbourhoods, and its population has been shaped by internationalisation (Deboosere et al., 2009).

We aimed to study the independent and combined associations between objective and subjective indicators of air pollution and cardiovascular and respiratory disease mortality, and specifically, ischemic heart disease (IHD), cerebrovascular diseases, and chronic obstructive pulmonary disease (COPD) excluding asthma mortality in the BCR. The link between these mortality causes and objective indicators of PM2.5 exposure has been well established (Landrigan, 2017), but evidence is absent for the subjective perception of air pollution, and for the interaction effect between subjective and objective air pollution indicators. Furthermore, we investigated the role of area-level socioeconomic position (SEP) in the associations between the exposures and mortality outcomes.

**2. Methods**

**2.1 Data design and study population**

We used data from the 2001 Belgian census linked to register mortality data during the follow-up period from the 1st of October 2001 until the 31st of December 2014. Data on causes of death was coded using the ICD-10 of the WHO (WHO, 2016). The Belgian census contains a large set of sociodemographic and socioeconomic indicators at an individual level for the total population officially residing in Belgium in 2001. Environmental data (i.e. ambient air pollution, noise pollution) were linked to the census using the official residential address. The study population consisted of adults aged 30 and above with official residential address in the BCR at baseline (2001).

**2.2 Mortality outcomes**

We focussed on cardiovascular diseases (ICD-10 codes I10-I70) and respiratory diseases (ICD-10 codes J00-J99) as underlying causes of death. We also looked at specific cardiorespiratory mortality outcomes: ischemic heart diseases (IHD) (ICD-10 codes I20-I25), cerebrovascular diseases (ICD-10 codes I60-I69), and chronic obstructive pulmonary disease (COPD) excluding asthma (ICD-10 codes J40-J44, J47). These ICD-10 codes were included based on earlier classification by Brunekreef et al. (2021). Mortality data was linked to the census data at the individual level by Statistics Belgium.

**2.3 Subjective perception of air pollution**

The subjective indicator consists of self-reported perceived air quality in the 2001 Belgian census. The reference person of the household was asked to rate the air quality in his/her neighbourhood according to his/her subjective perception on a three-point Likert scale, 1 “not pleasant”, 2 “satisfactory”, and 3 “very pleasant” (Figure S1)  As stated earlier in the introduction, we hypothesize that the mechanisms potentially linking poor air quality perception to poor health outcomes are related to stress-induced responses by annoyance or health concerns. Thus, we considered people reporting poor air quality as the exposed group, since they may be experiencing negative emotional responses due to air pollution. Therefore, for the analysis, we dichotomized the variable to “neutral or good” (reference category) versus “poor (i.e. not pleasant)”.

**2.4 Modelled air pollution estimates**

The objective indicator consists of residential annual mean concentrations of fine particulate matter, with aerodynamic diameter 2.5 micrometres (µm) or smaller (PM2.5), modelled at a high resolution (25 m). Estimates were provided by the Belgian Interregional Environment Agency (IRCEL-CELINE) (https://www.irceline.be/) and were based on interpolation-dispersion (RIO-IFDM) models. The IFDM model is a bi-gaussian model, where air pollution emissions are spatially and temporally distributed. The dispersion model uses traffic and industrial emission data, and meteorological data. This data is coupled to regional concentration levels from the land-use regression model RIO. The RIO model combines data from fixed air quality monitoring stations based on a land-use (CORINE) derived covariate (Lefebvre et al., 2013). The performance of air pollution exposure models has been exhaustively validated with cross-validation (leaving one out) and with independent measurement campaigns. The RIO model has been shown to be the most accurate way of mapping air pollution in Belgium (Hooyberghs et al., 2006; Janssen et al., 2008; Lefebvre & Vranckx, 2013). Annual mean concentrations of PM2.5 for the year 2005 were assigned to the residential address at baseline (2001). A map showing the annual mean concentrations of PM2.5 in the BCR is displayed in supplementary material (Figure S2).

In the analyses we also considered NO2, concentrations, and both pollutants were analysed separately. Due to the high correlation between both pollutants (0.98), bi-pollutant models were not conducted.

**2.5 Covariates**

Socioeconomic and sociodemographic information was gathered from the 2001 Belgian census. We considered age, sex, migration background [originating from Belgium/other high-income country (HIC)/low-middle income country (LMIC)] and household living arrangement (single/cohabitation with partner/other) as sociodemographic indicators, and housing tenure (owner/tenant) and educational level (tertiary /higher secondary/lower secondary/low or no education) as SEP indicators. Neighbourhood SEP was approximated as unemployment rate per census tract (i.e. the smallest geographical unit available for residential information) (Figure S3).

In additional analysis we included an indicator for residential noise pollution. We used 2016 estimates of daily average exposure to multi-exposure transportation (road/rail/air) noise levels (Lden), modelled in decibels (dB) at 10mx10m spatial resolution. Noise levels are measured from 17 permanent measurement stations in BCR, situated strategically around Brussels to capture noise from one single means of transportation. Noise levels were linked individually to the census data at a personal level by using official residential address (Brussels Environment, 2018).Click or tap here to enter text.

**2.6 Statistical analyses**

We conducted Spearman correlation analysis between both exposures (modelled air pollution estimates and subjective air pollution perception) and other living environment characteristics (unemployment per census tract and noise pollution). We analysed the associations between both exposures and cause-specific mortality outcomes using the Cox proportional hazard model with age as underlying time scale. Observations were censored at age at emigration, age at death from other causes, or age at the end of follow-up. Models were specified with increasing degree of covariate adjustment. Model 1 (the basic model) was stratified by sex to satisfy the proportional hazard assumption, tested with Schoenfeld residuals. Model 2 added individual-level covariates: migration background, educational level, housing tenure, and household living arrangement. Model 3 (full model) added the unemployment rate per census tract. To evaluate the linearity of the exposure-response association between PM2.5 exposure and mortality outcomes, we specified natural splines with 2 degrees of freedom in the full models, for each mortality outcome separately. We then assessed the improvement in the goodness-of-fit of this model compared to the full model with the linear term using a likelihood ratio test (LRT). Deviations from linearity occurred at high exposures, where the number of observations was lower (Figure S4). Moreover, significant deviations from linearity were only found for respiratory diseases. Therefore, results are expressed as hazard ratios (HRs) with 95% confidence intervals (95%CI) of 10 µg/m3 increments in PM2.5, and of reporting poor versus fair/good air quality perception.

We conducted single-exposure models of both exposures on each outcome. Then we fitted two-exposure models to explore the joint effects of PM2.5 and poor air quality perception on the mortality outcomes. The correlation between PM2.5 and subjective air pollution indicator was -0.29. Next, we included a multiplicative interaction term between both exposures to explore interaction, using LRT to evaluate significant interaction versus two-exposure model, for each mortality outcome separately.

To assess the robustness of our findings, we conducted several sensitivity analyses for the single-exposure models. We repeated our analyses by limiting our study population to individuals that 1) reported good or very good self-perceived health at baseline; 2) lived in the same census tract 10 years prior to baseline (1991-2001); 3) were aged 60 years and older. Furthermore, 4) we adjusted the models for noise pollution levels (Lden) (Rodriguez-Loureiro et al., 2021), and 5) using exposure to NO2 concentrations.

Finally, we explored effect modification by neighbourhood SEP. We categorised neighbourhood unemployment rate into tertiles. In single-exposure models, we included an interaction term between the exposures and neighbourhood SEP, separately for each outcome. We considered significant interaction when the LRTs comparing these models with the full models were significant. Finally, we conducted stratification by tertiles of neighbourhood unemployment rate.

We considered significant results with p-value smaller than 0.05. All analyses were conducted using the statistical program R 4.1.1. (R Core Team, 2017).

**3. Results**

Table 1 shows a detailed description of the study population at baseline and their residential environmental exposures, according to air quality perception at baseline [i.e. people who reported poor air quality (*n*=125,154, 28.6%), and who reported fair or good air quality (*n*=312,186, 71.4%)]. The study population consisted of 437,340 individuals officially residing in the BCR in 2001 aged 30 years and older. During follow-up (2001-2014), most deaths were due to CVD (*n*=22,821; 5.2%), including IHD (*n*=7,986; 1.8%) and cerebrovascular diseases (*n*=5,235; 1.2%). There was a higher proportion of deaths due to CVD in the group who reported fair or good air quality compared to those who reported poor air quality (5.5% vs. 4.6%, respectively). There were 8,572 deaths due to respiratory diseases (2.0%), and 3,456 (0.8%) due to COPD excluding asthma. The mean annual exposure to PM2.5 concentrations among those who reported poor air quality in their residential area was 19.58 (± 0.87) µg/m3, only slightly higher than those who reported fair or good air quality (mean = 19.10 ± 0.94 µg/m3). People who reported poor air quality had higher levels of unemployment in their census tracts (mean = 22.8, IQR = 17.2) compared to people who reported good air quality (mean = 18.4, IQR = 9.5). A greater proportion of individuals who reported fair or good air quality reported (very) good self-perceived health at baseline compared to those who reported poor air quality (67.9% vs. 60.3%). From the individuals who reported poor air quality, 30.8% had tertiary education and 24.8% had low or no education, whereas among those who reported fair or good air quality the share was 35.0% and 21.3%, respectively. Individuals reporting poor air quality originated more frequently from low- and middle-income countries than those who reported fair/good air quality (21.3% vs. 17.7%).

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| |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | | Table 1: Baseline characteristics of the study population, by air quality perception (n=437,340). Brussels Capital Region, 2001. | | | | | | |  | |  | People who reported poor air quality (N=125,154). | People who reported fair/good air quality (N=312,186) | Study population (N=437,340) | |  | Characteristic | Category | N (%) or mean (SD/IQR) | N (%) or mean (SD/IQR) | N (%) or mean (SD/IQR) | | Health Outcomes | Mortality cause (ICD-10 code) | Cardiovascular diseases (I10-I70) | 5,733 (4.6%) | 17,088 (5.5%) | 22,821 (5.2%) | |  |  | Ischaemic heart diseases (I20-I25) | 2,103 (1.7%) | 5,883 (1.9%) | 7,986 (1.8%) | |  |  | Cerebrovascular disease (I60-I69) | 1,278 (1.0%) | 3,957 (1.3%) | 5,235 (1.2%) | |  |  | Respiratory diseases (J00-J99) | 2,301 (1.8%) | 6,271 (2.0%) | 8,572 (2.0%) | |  |  | COPD excluding asthma (J40-J44, J47) | 1,039 (0.8%) | 2,417 (0.8%) | 3,456 (0.8%) | | Exposures | Modelled air pollutant concentrations | PM2.5 (µg/m3) | 19.6 (0.9) | 19.1 (0.9) | 19.2 (0.9) | | Covariates | Age |  | 50.6 (15.1) | 52.8 (15.8) | 52.2 (15.7) | |  | Sex | Female | 67,109 (53.6%) | 166,176 (53.2%) | 233,285 (53.3%) | |  |  | Male | 58,045 (46.4%) | 146,010 (46.8%) | 204,055 (46.7%) | |  | Education | Tertiary education | 38,550 (30.8%) | 109,349 (35.0%) | 147,899 (33.8%) | |  |  | Higher secondary education | 27,044 (21.6%) | 67,902 (21.8%) | 94,946 (21.7%) | |  |  | Lower secondary education | 28,536 (22.8%) | 68,567 (22.0%) | 97,103 (22.3%) | |  |  | Low/no education | 31,024 (24.8%) | 66,368 (21.3%) | 97,392 (22.3%) | |  | Migration background | Belgian | 75,324 (60.2%) | 200,791 (64.3%) | 276,115 (63.1%) | |  |  | Other HIC | 23,168 (18.5%) | 56,149 (18.0%) | 79,317 (18.1%) | |  |  | Turkish/Northern African/Other LMIC | 26,662 (21.3%) | 55,246 (17.7%) | 81,908 (18.7%) | |  | Housing tenure | Owner | 64,200 (51.3%) | 172,381 (55.2%) | 236,581 (54.1%) | |  |  | Tenant | 60,954 (48.7%) | 139,805 (44.8%) | 200,759 (45.9%) | |  | Living arrangement | Single | 47,789 (38.2%) | 114,228 (36.6%) | 162,017 (37.0%) | |  |  | Cohabiting/Married couple | 70,167 (56.1%) | 181,005 (58.0%) | 251,172 (57.4%) | |  |  | Other | 7,198 (5.8%) | 16,953 (5.4%) | 24,151 (5.5%) | |  | Unemployment% per census tract |  | 22.765 (10.341) | 18.473 (8.967) | 19.702 (9.580) | |  | Movers | Did not move | 68,598 (54.8%) | 173,636 (55.6%) | 242,234 (55.4%) | |  |  | Moved | 56,556 (45.2%) | 138,550 (44.4%) | 195,106 (44.6%) | |  | Subjectively perceived health | Good / very good | 75,408 (60.3%) | 211,922 (67.9%) | 287,330 (65.7%) | |  |  | Fair / Poor / Very poor | 49,746 (39.7%) | 100,264 (32.1%) | 150,010 (34.3%) | |  | Noise pollution | Lden (decibel, dB) | 50.829 (4.858) | 50.114 (5.397) | 50.319 (5.258) | | Note: All covariates (except unemployment% per census tract) are measured at an individual level. | | | | | | | | | | | |
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The results of the correlation analysis showed low to moderate correlations between the objective and the subjective indicators of air pollution exposure and the living environment indicators (Figure S5). The highest observed correlation was found between PM2.5 and neighbourhood SEP (r=0.45), after two pollutants, PM2.5 and NO2 (r=0.98).

Table 2 displays the results of single-exposure models showing the associations between both indicators of air pollution exposure and each mortality outcome, separately. In the basic model (Model 1) both exposures were associated with an increased mortality risk from all the causes of death studied. For each 10µg/m3 increment in PM2.5, the increase in the risk ranged from 56.5% (95%CI: 1.19-2.06) for cerebrovascular disease mortality, to 134.9% (95%CI: 1.68-3.28) for COPD excluding asthma mortality. For poor air quality perception, the strongest effect was observed for mortality due to COPD excluding asthma: 34.3% (95%CI:1.25-1.45). Both exposures showed a stronger relationship with respiratory disease mortality than with CVD mortality. After adjusting for individual level covariates (M2), the magnitude of the associations generally reduced. The associations with poor air quality perception only remained significant for IHD and COPD excluding asthma mortality. When neighbourhood SEP was added (M3), the associations further reduced, the relationship between PM2.5 and CVD (HR 1.10; 95CI%: 1.10-1.47) and IHD mortality (HR 1.52, 95CI%: 1.19-1.93) remained significant, with the association between PM2.5 and cerebrovascular disease mortality remained barely significant (HR 1.34; 95CI%: 1.00-1.80). Although the significance of the associations for PM2.5 and the other mortality outcomes was lost or barely significant, the direction of the effects remained positive. The association between poor air quality perception and COPD excluding asthma mortality remained significant (HR 1.23%, 95CI%: 1.15-1.33), whereas for other mortality outcomes the effects flattened. The weakest associations in M1 reduce close to the null in M3.

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| Table 2: Single-exposure models of the associations (HR and 95%CI) between air pollution exposure (10 µg/m3 increase in modelled PM2.5 estimates and poor subjective perception of air quality) and mortality outcomes. Brussels Capital Region, 2001-2014. | | | |
|  | M1 | M2 | M3 |
|  | HR (95%CI) | HR (95%CI) | HR (95%CI) |
| Cardiovascular diseases (CVD) |  |  |  |
| PM2.5 (µg/m3) | **1.635 (1.433-1.866)** | **1.442 (1.258-1.653)** | **1.273 (1.104-1.468)** |
| Poor air quality perception | **1.063 (1.032-1.095)** | 0.996 (0.940-1.055) | 0.980 (0.924-1.039) |
| Ischemic heart disease (IHD) |  |  |  |
| PM2.5 (µg/m3) | **2.216 (1.776-2.764)** | **1.823 (1.447-2.297)** | **1.515 (1.189-1.93)** |
| Poor air quality perception | **1.115 (1.061-1.173)** | **1.071 (1.019-1.126)** | 1.041 (0.990-1.096) |
| Cerebrovascular disease |  |  |  |
| PM2.5 (µg/m3) | **1.565 (1.187-2.063)** | **1.47 (1.107-1.951)** | **1.343 (1.00-1.804)** |
| Poor air quality perception | 1.021 (0.959-1.088) | 1.000 (0.939-1.066) | 0.986 (0.925-1.052) |
| Respiratory disease |  |  |  |
| PM2.5 (µg/m3) | **1.825 (1.473-2.262)** | **1.448 (1.157-1.813)** | 1.216 (0.961-1.539) |
| Poor air quality perception | **1.177 (1.122-1.235)** | 1.013 (0.912-1.126) | 0.996 (0.895-1.107) |
| COPD excluding asthma |  |  |  |
| PM2.5 (µg/m3) | **2.349 (1.68-3.284)** | **1.662 (1.163-2.377)** | 1.344 (0.923-1.956) |
| Poor air quality perception | **1.343 (1.249-1.445)** | **1.266 (1.177-1.362)** | **1.233 (1.145-1.328)** |
| Note: HR: Hazard Ratio, 95%CI: 95% Confidence Interval, PM2.5: Particulate matter with an aerodynamic diameter of <2.5 µm. Results were obtained by using Cox Proportional Hazards models, with age as the underlying time scale, for the follow-up period 2001-2014. M1 is stratified by sex, age as an underlying time scale. M2 is adjusted for individual level covariates, migration and education background, housing tenure, and living arrangement. M3 is furtherly adjusted for unemployment rate per census tract. Significant results are highlighted in bold. | | | |

Table 3 shows the results of the two-exposure models. We observed similar results compared to the full model (M3) for CVD, IHD and cerebrovascular disease mortality. However, for respiratory disease mortality, the effect of poor air quality perception became significant after adjustment for PM2.5 levels (HR 1.10; 95%CI: 1.04-1.15) and changed direction compared to the full model, indicating that the effect of the subjective indicator of air quality was confounded by modelled air pollution levels. For COPD excluding asthma mortality, the association with poor air quality perception did not change considerably compared to the full model (M3), whereas the magnitude of the association with PM2.5 reduced considerably after adjustment for subjective perception of air quality. We did not find evidence of an interaction between PM2.5 and subjective perception of air quality for any mortality outcome (*results not shown*).

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| Table 3: Two-exposure models of the associations (HR) and 95%CI between air pollution (10 µg/m3 increase in modelled PM2.5 estimates and poor subjective perception of air quality) on mortality outcomes. Brussels Capital Region, 2001-2014. | | |
|  | PM2.5 + poor air quality perception |
|  | HR (95%CI) |
| Cardiovascular diseases |  |
| PM2.5 (µg/m3) | **1.268 (1.097-1.465)** |
| Poor air quality perception | 1.005 (0.975-1.037) |
| Ischemic heart disease |  |
| PM2.5 (µg/m3) | **1.483 (1.160-1.896)** |
| Poor air quality perception | 1.028 (0.977-1.083) |
| Cerebrovascular disease |  |
| PM2.5 (µg/m3) | **1.369 (1.015-1.846)** |
| Poor air quality perception | 0.976 (0.914-1.042) |
| Respiratory disease |  |
| PM2.5 (µg/m3) | 1.128 (0.888-1.432) |
| Poor air quality perception | **1.097 (1.044-1.153)** |
| COPD excluding asthma |  |
| PM2.5 (µg/m3) | 1.127 (0.768-1.652) |
| Poor air quality perception | **1.230 (1.141-1.327)** |
| Note: HR: Hazard Ratio, 95%CI: 95% Confidence Interval, PM2.5: Particulate matter with an aerodynamic diameter of <2.5 µm. Results were obtained by using Cox Proportional Hazards models, with age as an underlying time scale, for the follow-up period 2001-2014. Models are stratified by sex, and adjusted for migration and education background, housing tenure, living arrangement, and for unemployment rate per census tract. Significant results are highlighted in bold. | |

Next, sensitivity analyses were conducted to assess the robustness of our findings in the single-exposure models (Table S1), by limiting our analyses to a healthy subpopulation (reported good or very good self-perceived health at the baseline), non-movers (living in the same census tract for 10 years prior to baseline), population aged 60+, and by further adjusting our models for noise pollution. The sensitivity analyses generally confirmed the results of our full models (M3). For non-movers, the older population, and further adjustment for noise pollution, we observed a significant effect of poor air quality perception on respiratory disease mortality, similar to the effect observed in the two-exposure model. When limiting our analyses to the baseline healthy subpopulation, the relationships between both exposures and mortality outcomes reduced and became non-significant, except for the association between PM2.5 with CVD mortality, which became slightly stronger compared to our full model (HR 1.35; 95%CI: 1.06-1.71). When assessing the associations between NO2 exposure to mortality outcomes, the results were consistent, but weaker, compared to the full model with PM2.5 exposure.

Finally, we explored effect modification by tertiles of unemployment rate per census tract as a proxy of neighbourhood SEP in the single-exposure models (Table 4). We observed a significant interaction between poor perception of air quality and unemployment rate for CVD and IHD mortality, and COPD excluding asthma mortality. When conducting the analysis by tertiles of unemployment rate, the association between PM2.5 and cerebrovascular disease mortality increased gradually with greater unemployment, showing the weakest effect in areas with lowest unemployment (Q1) (HR 1.03, 95%CI: 0.67-1.58), and the strongest effect in areas with highest unemployment rate (Q3) (HR 2.40, 95%CI: 1.11-5.20). For CVD and IHD mortality the pattern was less evident, with the strongest effect observed in Q2. For respiratory disease mortality, PM2.5 appeared to be harmful only in areas with the lowest unemployment (Q1) (HR 1.57; 95%CI:1.10-2.23). Similarly, for COPD excluding asthma mortality we observed a positive (yet non-significant) association with PM2.5 only in Q1 (HR 1.42; 95%CI:0.78-2.57). With poor air quality perception, no pattern across unemployment tertiles was observed with CVD mortality. However, for respiratory disease and COPD excluding asthma mortality there was a clear gradual pattern with increasing area-level deprivation. For instance, for mortality due to COPD excluding asthma, the risk increased from 12.3% (95%CI:0.96-1.31) in Q1 to 22.0% (95%CI:1.07-1.39) in Q2 and 32.4% (95%CI:1.18-1.49) in Q3.

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| Table 4: Stratified analyses of the associations between air pollution exposure (single-exposure models) and mortality outcomes, by tertiles of neighbourhood SEP (unemployment rate per census tract). Brussels Capital Region, 2001. | | | | |
|  | Wealthiest neighbourhoods | (Q2) | Most deprived neighbourhoods | p-value for interaction | |
| (Q1) | (Q3) |
|  | HR (95%CI) | HR (95%CI) | HR (95%CI) |
| Cardiovascular diseases |  |  |  |  | |
| PM2.5 (µg/m3) | 1.039 (0.839-1.286) | **1.457 (1.147-1.851)** | 1.265 (0.866-1.849) | 0.951 | |
| Poor perception of air quality | 1.041 (0.982-1.103) | 0.994 (0.944-1.048) | 0.99 (0.941-1.042) | **<0.001** | |
| Ischemic heart disease |  |  |  |  | |
| PM2.5 (µg/m3) | 1.295 (0.889-1.885) | **1.647 (1.104-2.457)** | 1.195 (0.644-2.216) | 0.269 | |
| Poor perception of air quality | 1.077 (0.974-1.191) | 1.014 (0.929-1.106) | 1.016 (0.935-1.103) | **<0.001** | |
| Cerebrovascular disease |  |  |  |  | |
| PM2.5 (µg/m3) | 1.025 (0.665-1.580) | 1.582 (0.956-2.62) | **2.402 (1.11-5.199)** | 0.067 | |
| Poor perception of air quality | 1.067 (0.949-1.2) | 0.929 (0.83-1.04) | 0.938 (0.841-1.046) | 0.087 | |
| Respiratory disease |  |  |  |  | |
| PM2.5 (µg/m3) | **1.565 (1.099-2.228)** | 0.751 (0.499-1.129) | 0.976 (0.529-1.798) | 0.185 | |
| Poor perception of air quality | 1.078 (0.98-1.186) | **1.089 (1.00-1.185)** | **1.134 (1.047-1.228)** | 0.007 | |
| COPD excluding asthma |  |  |  |  | |
| PM2.5 (µg/m3) | 1.418 (0.782-2.569) | 0.867 (0.461-1.629) | 0.939 (0.372-2.366) | 0.423 | |
| Poor perception of air quality | 1.123 (0.962-1.311) | **1.220 (1.074-1.387)** | **1.324 (1.176-1.491)** | **<0.001** | |
| Note: HR: Hazard Ratio, 95%CI: 95% Confidence Interval, PM2.5: Particulate matter with an aerodynamic diameter of <2.5 µm. Results were obtained by using Cox Proportional Hazards models, with age as the underlying time scale, for the follow-up period 2001-2014. Models are stratified by sex, and adjusted for migration and education background, housing tenure, living arrangement, and for unemployment rate per census tract. Q1; 4.4%-13.9%, Q2: 13.9%-21.8%, Q3: 21.8-56.3%. P-value for interaction obtained with Likelihood Ratio Test, comparing the single-exposure model (PM2.5 and subjective perception of air quality, separately) with model with interaction term between the exposure and unemployment rate in the census tract. Significant results are highlighted in bold. | | | | | |

**4. Discussion**

In our study on the Brussels Capital Region (BCR), being exposed to fine particulate matter (PM2.5) increased the risk for CVD mortality, while having a poor perception of air quality increased the risk for respiratory disease mortality, and more specifically, for COPD excluding asthma mortality. We found that both exposures, PM2.5 and subjective air quality perception, worked independently on the mortality outcomes studied, except for the association of poor air quality perception with respiratory disease mortality, that was confounded by exposure to PM2.5 levels. We observed suggestive effect modification by neighbourhood SEP: associations were generally stronger with increasing neighbourhood unemployment rate for PM2.5 and CVD mortality. The clearest gradual patterns were observed with PM2.5 and cerebrovascular disease mortality, and for poor perception of air quality and respiratory disease mortality.

Our research supports earlier studies showing that being exposed to higher PM2.5 levels increases the risk of CVD mortality (Alexeeff et al., 2021; Bont et al., 2022; Chen & Hoek, 2020). A recent meta-analysis on the effect of PM2.5 on CVD mortality showed a relative risk (RR) of 1.11 (95%CI: 1.03-1.18) per 10µg/m3 increase, along with increased risk for IHD mortality (RR: 1.16, 95%CI: 1.10-1.21) (Chen & Hoek, 2020). This is in line with our findings, although the magnitude of the effects was stronger in our study. We hypothesize that the marked urban morphology typical for the BCR, including high buildings causing the street canyon effect, together with the specific characteristics of the study population, e.g. more vulnerable individuals exposed to higher air pollution concentrations due to residential segregation in the BCR (Deboosere et al., 2009), may explain our stronger associations. For respiratory disease mortality and PM2.5 we found similar, although non-significant, associations to the results from the meta-analysis (RR: 1.10, 95%CI: 1.03-1.53) (Chen & Hoek, 2020). Our non-significant results were, however, indicating associations in the same direction even though the confidence interval indicated higher instability of the results.

To our best knowledge, this is the first study to investigate subjective air quality perception in relation to cardiorespiratory disease mortality using a population-based study. Most prior studies found a link between air pollution annoyance and respiratory diseases in adults, including rhinitis (Cesaroni et al., 2008; Jacquemin et al., 2007), asthma (Cesaroni et al., 2008), phlegm and shortness of breath (Jacquemin et al., 2007; Oglesby et al., 2000), and chest tightness (H. Orru et al., 2018). Only two studies investigated a potential effect of air pollution perception on CVDs, and results were mixed: one found a link between self-reported traffic intensity and higher prevalence of hypertension (Pitchika et al., 2017), whereas the other found no associations between air pollution annoyance and cardiovascular outcomes, including hypertension or heart disease (H. Orru et al., 2018).

Moreover, we hypothesized *a priori* that being exposed to higher PM2.5 levels and experiencing poor air quality would interact and exacerbate the risk of cardiorespiratory disease mortality. However, we found that exposures were independently associated with each outcome, except for the association between poor air quality perception and respiratory disease mortality, that was confounded by the exposure to PM2.5 levels. When using the subjective indicator, we are potentially also measuring other aspects of surroundings, as in odours, cleanness, and traffic intensity in the neighbourhood. Our findings are supported by previous research showing low correlations between objective and subjective measures of air pollution (K. Orru et al., 2018; Pelgrims et al., 2022; Pitchika et al., 2017). Furthermore, our findings support the message of earlier literature, that it is valuable to look at air pollution perception separately from objective air pollution exposure (Golbidi et al., 2015; Orru et al., 2018). Poor air quality perception did not interact with objective air pollution levels, and were independently associated with higher mortality risk. Thus, it is important to understand the holistic approach to environmental health. Air pollution has an objective existence, but when discussing air quality perception, it is socially meditated. An example of this was detected in heavily industrialized area, Teesside in England, with an objectively measured relatively clean air but perceived from a lay perspective as polluted and entailing health risks (Bush et al., 2001; Noël et al., 2021).

As found in the earlier literature, subjective perception of air pollution could be a valuable indicator to identifying populations at risk (Pelgrims et al., 2022). In our findings, limiting the analyses to a healthy subpopulation at baseline reduced most of the observed associations. We may speculate that this is due to reporting bias and selection effect, i.e. people suffering from respiratory diseases reporting poor air quality perception more frequently. This has been found in previous studies in both children and adult populations (Cesaroni et al., 2008; Kuehni et al., 2006). Moreover, two prior studies using path analysis showed the interrelatedness of air pollution annoyance, health risk perception, and self-reported symptoms and diseases (K. Orru et al., 2018; Stenlund et al., 2009). Hence, the results from this and previous studies suggest that awareness of health effects of air pollution can affect subjective perception of air quality. In addition, it is well known that poor air quality affects the respiratory system, whereas the link with cardiovascular diseases may be less clear for the lay public (Noël et al., 2021). The mechanisms through which air pollution contributes to CVD development are latent (e.g., exacerbating the risk of developing diabetes mellitus or hypertension), and often commonly associated with lifestyle choices rather than with air pollution (Rajagopalan et al., 2018).

We found that, generally, people in more deprived neighbourhoods of the BCR carried the largest burden of objective and subjective air pollution exposure. Our results are in line with earlier research showing the importance of SEP in determining the harmfulness of air pollution (Hajat et al., 2021), and further show that this may also apply to individuals reporting poor air quality (Hajat et al., 2015). Brussels presents strong residential segregation, with socioeconomically deprived groups residing in inner-city areas with higher levels of air pollution, mainly due to higher traffic intensity or more intense indoor burning of fossil fuels (Noel et al., 2020). In our study, individuals reporting poor air quality lived in areas with higher unemployment rates and more frequently had low or no education. In a previous study, individuals with lower income were more likely to perceive the air quality in their living surroundings as poor (Kim et al., 2012). Societal groups with low income may present higher susceptibility to air pollution exposure, due to a greater risk of underlying chronic diseases, but also due to limited access to resources to cope with harmful exposures. Further, societal groups with low income may have lower awareness of the air pollution exposure, and the consequences of it. People with higher education have more resources to cope with harmful environmental conditions, for instance, by moving to other less polluted parts of the city. In contrast, low educated groups with poor air quality perception may be unable to cope with high air pollution concentrations at their residence. In earlier research, a higher level of education is seen as explaining a heightened perception of pollution, even though their objective air pollution exposure is lower. The more highly educated have a better awareness of the bad consequences of air pollution, thus, they might be more sensitive to it in their surroundings (Noel et al., 2020; Orru et al., 2018).

Some methodological considerations should be taken into account for the interpretation of the findings from this study. The rich dataset is a strength of our study: we had individual information on objective and subjective exposure to air pollution at a population-wide level. Also, we had a long mortality follow-up period and information on relevant sociodemographic and socioeconomic indicators, and on other environmental indicators, including noise pollution. However, we should acknowledge a few limitations. We used time-fixed information of air pollution concentrations for the year 2005, i.e. the earliest year for which high resolution air pollution estimates were developed in Belgium. It is likely that air pollution concentrations have decreased throughout the follow-up period following the introduction of air quality directives, as has been observed in other European countries. However, we assumed that the spatial distribution remained stable in the years under study. Another limitation of our study is that we may have incurred exposure misclassification, since the exposure data was assigned to the participants’ residential address at baseline, and we did not have continuous information on residential mobility. Available census data for 1991 allowed however for comparing residential addresses and identify non-movers between 1991 and 2001. In this way, we could repeat our analyses for a subsample of individuals who did not move 10 years prior to the start of the follow-up (2001) which showed that results did not change substantially. We did not have information about lifestyle factors (e.g., smoking habits or body mass index), which could influence the associations studied, especially regarding perceived air quality (Oglesby et al., 2000).

**5. Conclusion**

Our findings suggest that exposure to PM2.5 was associated with CVD mortality, and poor air quality perception with respiratory disease mortality, especially mortality due to COPD excluding asthma in the Brussels Capital Region (BCR). Our research fills a knowledge gap by combining objective and subjective air pollution indicators in the study with mortality outcomes, using a population-based study.

The findings of this study add to a research gap on the combined effect of subjective and objective exposure to air pollution on cardiorespiratory mortality, whilst considering socio-economic differences. When looking at similar studies previously conducted, we add more insight on the subjective perception of air quality by considering the socio-demographic differences of the populations who have reported poor air quality, as seen, people with low or no education more frequently report poor air quality, and people who originate from low- and middle-income countries.

Future research should investigate the mechanisms linking poor air quality perception on health and confirm whether these operate independently from objective air pollution levels. The results by SEP encourage the formulation of policies that reduce the overall pollution load in the BCR while simultaneously implementing targeted policies in more deprived neighbourhoods, considering the heavier burden of poor air quality exposure they carry.

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| Table S1: Sensitivity analyses | | | | |  |
|  | 1) Healthy starting population | 2) Non-movers | 3) Age: 60+ | 4) Noise pollution | 5) NO2 exposure, full model |
|  | HR (95%CI) | HR (95%CI) | HR (95%CI) | HR (95%CI) | HR (95%CI) |
| Cardiovascular diseases |  |  |  |  |  |
| PM2.5 (µg/m3) | **1.137 (1.008-1.282)** | **1.090 (1.008-1.178)** | **1.110 (1.029-1.197)** | **1.112 (1.034-1.195)** |  |
| Poor air quality perception | 0.974 (0.919-1.032) | 1.021 (0.987-1.056) | 1.016 (0.983-1.050) | 1.011 (0.980-1.042) |  |
| NO2 (µg/m3) |  |  |  |  | **1.043 (1.016-1.071)** |
| Ischemic heart disease |  |  |  |  |  |
| PM2.5 (µg/m3) | 1.157 (0.938-1.427) | **1.209 (1.057-1.383)** | **1.224 (1.074-1.395)** | **1.199 (1.060-1.357)** |  |
| Poor air quality perception | 0.956 (0.866-1.055) | 1.031 (0.974-1.091) | 1.049 (0.992-1.109) | 1.038 (0.986-1.092) |  |
| NO2 (µg/m3) |  |  |  |  | **1.057 (1.01-1.106)** |
| Cerebrovascular disease |  |  |  |  |  |
| PM2.5 (µg/m3) | 1.162 (0.913-1.480) | 1.101 (0.938-1.292) | 1.140 (0.976-1.331) | 1.148 (0.988-1.335) |  |
| Poor air quality perception | 0.986 (0.877-1.108) | 1.002 (0.93-1.075) | 0.981 (0.915-1.050) | 0.987 (0.925-1.052) |  |
| NO2 (µg/m3) |  |  |  |  | **1.067 (1.001-1.127)** |
| Respiratory disease |  |  |  |  |  |
| PM2.5 (µg/m3) | 0.997 (0.799-1.246) | 1.064 (0.935-1.212) | 1.052 (0.929-1.191) | 1.056 (0.936-1.191) |  |
| Poor air quality perception | 0.989 (0.890-1.100) | **1.099 (1.041-1.161)** | **1.087 (1.031-1.145)** | **1.097 (1.045-1.152)** |  |
| NO2 (µg/m3) |  |  |  |  | 1.031 (0.987-1.077) |
| COPD excluding asthma |  |  |  |  |  |
| PM2.5 (µg/m3) | 1.097 (0.746-1.612) | 1.159 (0.939-1.430) | 1.100 (0.898-1.346) | 1.115 (0.920-1.351) |  |
| Poor air quality perception | 1.102 (0.926-1.311) | **1.245 (1.145-1.354)** | **1.184 (1.092-1.285)** | **1.231 (1.143-1.326)** |  |
| NO2 (µg/m3) |  |  |  |  | 1.052 (0.981-1.127) |
| Note: HR: Hazard Ratio, 95%CI: 95% Confidence Interval, PM2.5: Particulate matter with an aerodynamic diameter of <2.5 µm. Results were obtained by using Cox Proportional Hazards models, with age as the underlying time scale, for the follow-up period 2001-2014. 1) People who have reported good or very good self-perceived health at the baseline. 2) The living commune has remained the same between the baseline and March 1991. 3) People above 60 years old at the baseline. 4) M3 further adjusted for noise pollution. 5) M3 with NO2 as an exposure. Significant results are highlighted in bold. | | | | | |

**Figure S1**: Spatial distribution of air quality perception in the Brussels Capital Region, in 2001

A picture containing text, plant, flower

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**Figure S2:** Annual mean concentrations of PM2.5 and monitoring station location in the Brussels Capital Region, in 2005

Chart

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**Figure S3**: Spatial distribution of socio-economic position (unemployment percentage per statistical sector) in the Brussels Capital Region, in 2001

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Figure S4: Splines (HR: Hazard Ratio)

Diagram, engineering drawing

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Figure S5: Correlation matrix

Chart, bubble chart

Description automatically generated