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RESEARCH ARTICLE

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# Effects of traffic-related air and noise pollution exposure on allergic diseases in the elderly: an observational study

Sofia Tagliaferro[a,b], Federico Pirona[a,c], Salvatore Fasola[d], Ilaria Stanisci[a], Giuseppe Sarno[a], Sandra Baldacci[a], Claudio Gariazzo[e], Gaetano Licitra[f,g], Antonino Moro[h], Camillo Silibello[i], Massimo Stafoggia[j], Giovanni Viegi[a*], Sara Maio[a*] and on behalf of BEEP and BIGEPI groups[#,†]

[a]Institute of Clinical Physiology (IFC), National Research Council (CNR), Pisa, Italy; [b]Department of Diagnostics and Public Health, University of Verona, Verona, Italy; [c]Department of Statistics, Computer Science, Application, University of Florence, Florence, Italy; [d]Institute of Translational Pharmacology, National Research Council, Palermo, Italy; [e]National Institute for Insurance against Accidents at Work (INAIL)-Department of Occupational & Environmental Medicine, Rome, Italy; [f]Environmental Protection Agency-Tuscany Region, Florence, Italy; [g]Institute for Chemical-Physical Processes (IPCF), National Research Council (CNR), Pisa, Italy; [h]IPOOL srl, Pisa, Italy; [i]ARIANET srl, Milan, Italy; [j]Department of Epidemiology, Lazio Regional Health Service/ASL, Rome, Italy

**ABSTRACT**

**Introduction:** Traffic-related air and noise pollution are important public health issues. The aim of this study was to estimate their effects on allergic/respiratory outcomes in adult and elderly subjects.

**Materials and methods:** Six hundred and forty-five subjects living in Pisa (Tuscany, Italy) were investigated through a questionnaire on allergic/respiratory symptoms and diseases. Traffic-related air pollution and noise exposures were assessed at residential address by questionnaire, modelled annual mean $NO_2$ concentrations (1 km and 200 m resolution), and noise level over a 24-h period (Lden). Exposure effects were assessed through logistic regression models stratified by age group (18–64 years, ≥65 years), and adjusted for sex, educational level, occupational exposure, and smoking habits.

**Results:** 63.6% of the subjects reported traffic exposure near home. Mean exposure levels were: 28.24 (±3.26 *SD*) and 27.23 (±3.16 *SD*) μg/m³ for $NO_2$ at 200 m and 1 km of resolution, respectively; 57.79 dB(A) (±6.12 *SD*) for Lden. Exposure to vehicular traffic (by questionnaire) and to high noise levels [Lden ≥ 60 dB(A)] were significantly associated with higher odds of allergic rhinitis (OR 2.01, 95%CI 1.09–3.70, and OR 1.99, 95%CI 1.18–3.36, respectively) and borderline with rhino-conjunctivitis

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**CONTACT** Sofia Tagliaferro sofia.tagliaferro@hotmail.it Pulmonary Environmental Epidemiology Unit, CNR Institute of Clinical Physiology, Via Trieste 41, Pisa, 56126, Italy

*These authors are to be considered joint senior authors.

[#]*BEEP group:* Sandra Baldacci, Sara Maio, Giovanni Viegi (Institute of Clinical Physiology (IFC), National Research Council (CNR), Pisa, Italy); Salvatore Fasola, Stefania La Grutta (Institute of Translational Pharmacology, National Research Council, Palermo, Italy); Carla Ancona, Simone Bucci, Francesca de' Donato, Paola Michelozzi, Matteo Renzi, Matteo Scortichini, Massimo Stafoggia (Department of Epidemiology, Lazio Regional Health Service/ASL, Rome, Italy); Nicolàs Zengarini (Regional Public Health Observatory, ASL TO3, Turin, Italy); Annamaria Colacci, Federica Parmagnani, Andrea Ranzi (Regional Agency for Prevention, Environment and Energy of Emilia-Romagna, Bologna, Italy); Laura Bonvicini, Serena Broccoli, Paolo Giorgi Rossi, Marta Ottone (Reggio Emilia AUSL-IRCCS, Reggio Emilia, Italy); Lucia Bisceglia, Antonio Chieti (Strategic Regional Health and Social Agency of Puglia, Bari, Italy); Achille Cernigliaro, Salvatore Scondotto (Department of Health Services and Epidemiological Observatory, Regional Health Authority of Sicily Region, Palermo, Italy); Michela Bonafede, Claudio Gariazzo, Alessandro Marinaccio (INAIL-Department of Occupational & Environmental Medicine, Rome, Italy); Giuseppe Brusasca, Giuseppe Calori, Sandro Finardi, Alessandro Nanni, Nicola Pepe, Paola Radice, Camillo Silibello, Gianni Tinarelli, Francesco Uboldi (ARIANET S.r.l., Milan, Italy); Paola Angelini (Regione ER, Bologna, Italy); Stefania Argentini, Roberto Sozzi (CNR-ISAC, Rome, Italy); Sergio Bonomo, Francesco Forastiere (CNR-IRIB, Palermo, Italy); Giuseppe Carlino (SIMULARIA, Turin, Italy); Moreno Demaria (Department of Environmental Epidemiology, Piedmont Environmental Protection Agency, Turin, Italy); Claudia Galassi, Enrica Migliore (CPO, Turin, Italy); Gaetano Licitra (Environmental Protection Agency-Tuscany Region, Florence, Italy; Institute for Chemical-Physical Processes (IPCF), National Research Council (CNR), Pisa, Italy); Antonino Moro (IPOOL srl, Pisa, Italy).

[†]BIGEPI group: Sandra Baldacci, Sara Maio, Giuseppe Sarno, Ilaria Stanisci, Sofia Tagliaferro, Giovanni Viegi (Institute of Clinical Physiology (IFC), National Research Council (CNR), Pisa, Italy); Salvatore Fasola, Stefania La Grutta (Institute of Translational Pharmacology, National Research Council, Palermo, Italy); Carla Ancona, Lisa Bauleo, Giulia Cesaroni, Paola Michelozzi, Matteo Renzi, Massimo Stafoggia (Department of Epidemiology, Lazio Regional Health Service/ASL, Rome, Italy); Giuseppe Costa, Nicolás Zengarini (Regional Public Health Observatory, ASL TO3, Collegno, Turin); Simone Giannini, Andrea Ranzi (Regional Agency for Prevention, Environment and Energy of Emilia-Romagna, Bologna, Italy); Letizia Bartolini, Paolo Giorgi Rossi, Marta Ottone (Reggio Emilia AUSL-IRCCS, Reggio Emilia, Italy); Nicola Caranci, Chiara Di Girolamo (Regional Health and Social Agency of the Emilia-Romagna, Bologna, Italy); Lucia Bisceglia (Strategic Regional Health and Social Agency of Puglia, Bari, Italy); Achille Cernigliaro, Salvatore Scondotto (Department of Health Services and Epidemiological Observatory, Regional Health Authority of Sicily Region, Palermo, Italy); Francesca Locatelli, Pierpaolo Marchetti, Alessandro Marcon, Jessica Miotti, Lorena Torroni, Giuseppe Verlato (Department of Diagnostics and Public Health, University of Verona, Verona, Italy); Claudio Gariazzo, Alessandro Marinaccio, Stefania Massari (INAIL-Department of Occupational & Environmental Medicine, Rome, Italy); Camillo Silibello, Gianni Tinarelli (ARIANET S.r.l., Milan, Italy).

(OR 2.20, 95%CI 0.95–5.10, and OR 1.76, 95%CI 0.91–3.42, respectively) only in the elderly. No significant result emerged for $NO_2$.
**Conclusions:** Our findings highlighted the need to better assess the effect of traffic-related exposure in the elderly, considering the increasing trend in the future global population's ageing.

**HIGHLIGHTS**

- Global population is ageing.
- Allergic diseases are globally widespread even on adult population.
- The susceptibility due to ageing may increase the impact of air pollution on the elderly.
- Traffic-related air and noise pollution affects allergic status of the elderly.

## Introduction

Vehicular traffic is the main source of ambient air pollution and environmental noise. Both are important public health issues [1], even though the negative impacts on human health of noise pollution are less known and likely underestimated [2]. Consistent associations of air pollution with respiratory and cardiovascular diseases have been reported, whereas noise pollution has been mainly associated with psychophysics disorders, as well as well-being [1–3].

Rapid urbanization, industrialization, and demand for mobility have increased the population exposed to air pollution and urban noise [2,4]. The World Health Organization (WHO) recently published guidelines to provide recommendations for protecting human health from environmental noise [1] and from air pollution [5]. Despite this, about 20% of the European Union (EU) population is exposed to harmful traffic noise levels and up to 96% to levels of fine particulate matter above the 2021 WHO guidelines [2,6].

The number of elderly people and life expectancy is increasing, with a consequent increase in the incidence of many illnesses, including allergic diseases [7]. Recent evidence showed that asthma prevalence is increasing in the elderly population [8,9]. On the other hand, information on allergy prevalence in the elderly population is scanty [10].

Elderly people are particularly vulnerable and susceptible to the detrimental effects of air pollution due to pre-existing diseases, changes in lung structure and function determined by physiological ageing, exposure to smoking, past occupational and environmental exposure history, possibly affecting the cardiovascular and respiratory systems [9,11]. The few epidemiological studies carried out on the long-term effects of air pollution in the elderly showed higher risks of Chronic Obstructive Pulmonary Disease (COPD), lung function decline [12,13], cough [14], and elevated pulmonary inflammation [15].

Studies on the association between noise pollution, as a marker of traffic, and respiratory troubles in the elderly population are even fewer [16]. Indeed, the few studies conducted on the adult population have provided contrasting results: on one side, no significant association was found in a study investigating the role of traffic noise on asthma morbidity in three European cohorts [16]; on the other side, more recent studies found associations between noise and the incidence of asthma and COPD [17,18], or prevalence of respiratory symptoms and asthma [19].

New epidemiological research on allergy in the elderly is largely needed: diagnosis, assessment, and management of allergy are influenced by age-specific confounding factors that need to be taken into account [20].

In this framework, the 'Big data in Environmental and occupational EPidemiology' (BEEP) and the 'Use of BIG data for the evaluation of the acute and chronic health Effects of air Pollution in the Italian population' (BIGEPI) Italian projects, co-funded by the National Institute for Insurance against Accidents at Work (INAIL), were designed. Their purpose was to investigate the health effects of air pollution, meteorological and noise parameters on the Italian general population through the integration of national data, including land use, satellite, modelled meteorological fields and atmospheric composition variables, mortality, hospitalizations, morbidity, work injuries and commuting accidents [21–24].

As an added value, BEEP and BIGEPI projects have also provided the unique opportunity to evaluate the long-term air pollution and noise effects on a general population sample participating in an analytical epidemiological survey, by linking air pollutant and noise levels estimated at the residential address to the individual respiratory/allergic health data, taking also into account other risk factors.

The aim of this study was to estimate the associations of air and noise pollution with allergic/respiratory symptoms and diseases in adults living in Pisa, Tuscany, Italy, especially focusing on the elderly.

## Materials and methods

### *Study population*

Between 1985 and 2011, the Pulmonary Environmental Epidemiology Unit of the Institute of Clinical Physiology of the Italian National Research Council (IFC-CNR) performed three epidemiological surveys on a general population sample living in the urban/suburban area of Pisa/Cascina [25,26]. The surveys aimed at assessing the health effects of outdoor air pollution, focusing on respiratory and allergic conditions. The sample was selected using a multistage stratified family-cluster design. Detailed information on population characteristics and methods is available elsewhere [25,26].

In this paper, we focused on the subjects aged ≥18 years, living in the urban area of Pisa ($n=645$), who participated in the third survey (PI3), performed in 2009–2011.

Information on respiratory symptoms/diseases, comorbidities, environmental exposure, and risk factors was collected through a standardized interviewer-administered questionnaire, developed within the PI3 survey [24,26].

The PI3 study protocol, patient information sheet, and consent form were approved by the Pisa University Hospital Ethics Committee (Prot. no. 23887, 16 April 2008). Each subject provided a signed consent form before her/his participation.

### Environmental exposure

Traffic exposure was assessed with two different approaches: (a) information about exposure to vehicular traffic reported by questionnaire; (b) environmental modelling for either nitrogen dioxide ($NO_2$) or noise levels.

#### Traffic-related exposure by questionnaire

Information about vehicular traffic exposure was obtained through questionnaire using the following question: 'How often do cars pass in the proximity of your house?' (answer's options: 'constantly', 'frequently', 'seldom' or 'never'). A dichotomous variable was derived: presence of exposure ('Yes'), if the subject reported 'constantly' or 'frequently'; absence of exposure ('No'), if the subject reported 'seldom' or 'never'.

#### $NO_2$ exposure

The annual average $NO_2$ concentrations for the period 2013–2015 were estimated for each individual at the residential level through an integrated approach coupling a chemical transport model (CTM) with machine learning techniques; the estimations of $NO_2$ exposure were provided at two spatial resolutions (1 km and 200 m) [21,27,28]. The entire process is described elsewhere [27,28].

Briefly, an air quality modelling system (AQMS) based on the CTM Flexible Air quality Regional Model (FARM) was used to simulate the daily $NO_2$ concentration fields at a spatial resolution of 5 km for the period 2013–2015 over the entire national territory. AQMS included modules aimed at producing meteorological fields and related turbulence parameters, processing data from emission inventories, the dispersion and chemical transformations of pollutants, and accounting for the contribution to pollution levels from the surrounding areas. The concentrations produced by FARM, together with other spatial-temporal data, such as population, land use, surface greenness, and road networks, were used as predictors in a Machine Learning Random Forest (MLRF) algorithm to downscale daily concentrations at higher resolution (1 km) over the national territory and urban scale (200 m) [27,28].

The model performance was assessed by using a 10-fold cross-validation procedure comparing predicted values with actual measurements not included in the training phase: cross-validated $R^2$ were 0.60 for $NO_2$ at 1 km and 0.62 for $NO_2$ at 200 m resolution, indicating good predictive properties of the model in places with a lack of observations [27,28].

The daily series of exposure levels estimated for $NO_2$ concentrations were linked to the subjects' residential addresses, according to their spatial locations: then, the mean annual average exposure level was calculated for the year 2013, being the closest year to the epidemiological survey period.

#### Noise level exposure

A map of traffic noise for the Municipality of Pisa was developed to estimate the exposure of inhabitants. It is an update of the previous traffic noise map calculated for the year 2008 [29–31], since many areas had undergone relevant changes in terms of both traffic and morphological conditions related to the installation of noise barriers, round abouts, and new settlements.

To assess the influence of these changes, a specific campaign of noise (through sound level meters) and traffic (traditional count of light, heavy vehicles, and motorcycles) measurements was carried out in Pisa, combined with an innovative method to estimate traffic volumes. This method utilized data gathered through Google API (Application Programming Interface) as input for noise emission models [32]. In this approach, travel times of road links were acquired through Google API and appropriate delay functions of links were used to estimate traffic volumes [32].

The findings of the measuring campaigns, as well as the traffic data collected in the period 2012–2018, allowed the update of the traffic flows of the entire municipal road network.

The NMPB 2008 calculation model [33], which considers two different categories of vehicles (light and heavy), was used to update the noise map of the Municipality of Pisa, based on the new traffic volumes.

To estimate the noise levels, the acoustic model required: the geographic characterization of the study area (through the description of the digital ground model and its acoustic characteristics), the definition of the receivers (including building heights) and any obstacles to sound propagation, the acoustic emission of sound sources, the implemented average speed and traffic volume of each road link [33,34]. The calibration of the model was performed using noise levels measured during the experimental campaign.

The sound levels were estimated at the participants address, applying the VBEB method [35], to calculate the maximum and average exposure levels according to the 2002/49/EC Directive [36]. The VBEB method allows assigning exposure levels to inhabitants, simulating a crown of receivers around building façades.

The annual mean of daily noise levels [Lden: indicator of noise level based on energy equivalent noise level over a 24-h period with a penalty of 10 dB(A) for night noise and a penalty of 5 dB(A) for evening noise, determined over all the days of a year] was linked to the residential addresses of the subjects according to their spatial locations.

Noise levels were expressed using A decibel [dB(A)] as unit of measurement, i.e. an indicator of the relative loudness of sounds in air as perceived by human ears.

### *Health outcomes by questionnaire*

The following respiratory/allergic outcomes were derived from the standardized questionnaire:

i. asthma symptoms/diagnosis: if the subjects reported asthma confirmed by a physician, or attacks of shortness of breath with wheezing or whistling in the last 12 months, apart from common colds, or asthma attacks in the last 12 months, apart from common colds;
ii. allergic rhinitis symptoms/diagnosis: if the subjects reported nasal allergies, including hay fever, or problems with sneezing or a runny or blocked nose in the last 12 months, apart from common colds or flu;
iii. rhino-conjunctivitis symptoms: if subjects reported problems with sneezing or a runny or blocked nose with itchy or watery eyes in the last 12 months, apart from common colds or flu.

### *Potential confounders*

Information on the following variables was collected from the standardized questionnaire: sex, age (categorized as 18–64 and ≥65 years), education level (0–8 years of education, 9–13 years, >13 years), smoking habits (non-smokers, if the subjects had never smoked for at least one year; ex-smokers, if the subjects had smoked before the survey, but did not smoke at the moment of the survey; smokers, if the subjects currently smoked at least one cigarette daily), and occupational exposure (subjects exposed to fumes, gases, dusts or chemicals in the working environment during their lifetime; subjects never exposed at work).

### *Statistical analyses*

Statistical analyses were stratified by age group, to evaluate the relationship between traffic exposure and health outcomes in adults (18–64 years) and in the elderly (≥65 years), separately. For each outcome, the prevalence was assessed as the ratio (%) of the number of cases to the total population at the time of the PI3 survey.

The characteristics of the study sample were summarized as mean and standard deviation (*SD*), minimum and maximum for continuous variables, and percentage (%) for categorical variables. Comparisons among groups were performed through analysis of variance for continuous variables and chi-square test for categorical variables.

The pollutant concentrations and noise levels were summarized through the mean and *SD*, minimum, and maximum; correlations between $NO_2$ and Lden were assessed using Spearman's correlation coefficients.

To estimate the relationship between traffic-related exposure and the odds of respiratory/allergic symptoms/diagnosis, multivariable logistic regression models stratified by age group were run, adjusting for sex, educational level, smoking habits, and occupational exposure.

Traffic-related exposure was assessed as follows:

a. exposure to vehicular traffic from the questionnaire (yes, no);
b. exposure to 1 μg/m$^3$ increase in the annual mean concentration of $NO_2$ at a spatial resolution of 200 m and 1 km;
c. exposure to average noise level over a 24-h period [Lden < 60 dB(A), and Lden ≥ 60 dB(A)]; the cut-off of 60 dB(A) was considered as it corresponds to the 2$^{nd}$ tertile, so identifying the higher population exposure level and corresponding to the cut-off level used by Cai et al. [16].

The results were expressed as odds ratio (OR) and 95% confidence interval (CI). The significance level was set at $p<0.05$, while $p$-values between 0.05 and 0.1 were considered as borderline significant.

The statistical analyses were carried out using the SPSS (Statistical Package for Social Science) software version 26 (IBM Corp, Armonk, NY, USA).

## Results

The study sample consisted of 645 subjects (18–64 years: 57.7%; ≥65 years: 42.3%), with a mean age of 58 years (±18 years): of them, 53.8% were female, 52.9% had a low educational level (0–8 years), 53% were current or ex-smokers and 42.8% reported exposure to fumes/gases/dusts at work. Further, 63.6% reported vehicular traffic exposure at residential level. Compared to adults, the elderly subjects had a significantly lower educational level (0–8 years of education: 78.4 *vs.* 34.1%) and were less frequently current smokers (8.1 *vs.* 23.7%) (Table 1).

The mean exposure levels of the overall population were: 28.24 (±3.26 *SD*) and 27.23 (±3.16 *SD*) μg/m$^3$ for $NO_2$ at 200 m and 1 km of resolution, respectively, and 57.79 dB(A) (±6.12 *SD*) for noise level. Elderly subjects were significantly more exposed to traffic assessed by questionnaire (72.2 *vs.* 57.3%), $NO_2$ concentration at 200 m of resolution (28.66 ± 3.37 *vs.* 27.93 ± 3.15 μg/m$^3$), and noise levels (58.72 ± 5.72 *vs.* 57.10 ± 6.32 dB(A); ≥60 dB(A): 45.4 *vs.* 36.0%) (Table 1).

Overall, the prevalence rates of health outcomes were: 5.9, 17.9, and 36.7% for asthma, rhino-conjunctivitis, and allergic rhinitis symptoms/diagnosis, respectively. No significant difference emerged for respiratory symptoms/diseases prevalence between the age groups (Figure 1).

The air pollutant-noise correlation matrix showed a moderate positive correlation between $NO_2$ at 1 km and at 200 m resolution (0.449) and a low positive correlation between $NO_2$ at 200 m resolution and noise level (0.261). No significant correlation was found between $NO_2$ at 1 km and noise level (Table 2).

Traffic exposure assessed by questionnaire and model-derived measures of air and noise pollution were compared: subjects reporting exposure to vehicular traffic by questionnaire resulted significantly

**Table 1.** Descriptive characteristics and traffic-related exposure of the total population sample and by age group (%).

| Descriptive characteristics | Total sample ($n=645$) | Age group: 18–64 years ($n=372$; 57.7%) | Age group: ≥65 years ($n=273$; 42.3%) | $p$-Value |
|---|---|---|---|---|
| Sex (%) | | | | |
| Male | 46.2 | 47.3 | 44.7 | 0.509 |
| Female | 53.8 | 52.7 | 55.3 | |
| Age (years) | | | | |
| Mean ± *SD* | 58.06 ± 18.32 | 45.51 ± 13.28 | 75.17 ± 6.70 | **<0.001** |
| Min–max | 18–103 | 18–64 | 65–103 | |
| Education level (%) | | | | |
| 0–8 years | 52.9 | 34.1 | 78.4 | **<0.001** |
| 9–13 years | 31.5 | 40.9 | 18.7 | |
| >13 years | 15.7 | 25.0 | 2.9 | |
| Smoking habits (%) | | | | |
| Smoker | 17.1 | 23.7 | 8.1 | **<0.001** |
| Ex-smoker | 36.0 | 33.1 | 39.9 | |
| Non-smoker | 47.0 | 43.3 | 52.0 | |
| Occupational exposure (%) | | | | |
| Exposed | 42.8 | 42.7 | 42.9 | 0.977 |
| Not exposed | 57.2 | 57.3 | 57.1 | |
| Traffic-related exposure | | | | |
| Traffic exposure—*Q* (%) | | | | |
| Exposed | 63.6 | 57.3 | 72.2 | **<0.001** |
| Not exposed | 36.4 | 42.7 | 27.8 | |
| Air pollution | | | | |
| $NO_2$ (200 m resolution) (μg/m$^3$) | | | | |
| Mean ± *SD* | 28.24 ± 3.26 | 27.93 ± 3.15 | 28.66 ± 3.37 | **0.005** |
| Min–max | 17.49–38.90 | 17.49–37.05 | 18.32–38.90 | |
| $NO_2$ (1 km resolution) (μg/m$^3$) | | | | |
| Mean ± *SD* | 27.23 ± 3.16 | 27.21 ± 3.21 | 27.25 ± 3.09 | 0.855 |
| Min–max | 10.79–36.32 | 10.79–36.32 | 11.94–36.32 | |
| Noise pollution | | | | |
| Lden [dB(A)] | | | | |
| Mean ± *SD* | 57.79 ± 6.12 | 57.10 ± 6.32 | 58.72 ± 5.72 | **0.001** |
| Min–max | 33.50–71.30 | 33.50–69.60 | 43.30–71.30 | |
| Noise exposure (%) | | | | |
| Lden ≥60 dB(A) | 40.0 | 36.0 | 45.4 | **0.016** |
| Lden <60 dB(A) | 60.0 | 64.0 | 54.6 | |

*SD*: standard deviation; *Q*: through questionnaire; $NO_2$: nitrogen dioxide; Lden: day-evening-night noise level as described in the text; dB(A): A-weighted decibels, an expression of the relative loudness of sounds in air as perceived by human ears.
In bold the statistically significant values ($p$-value ≤ 0.050).

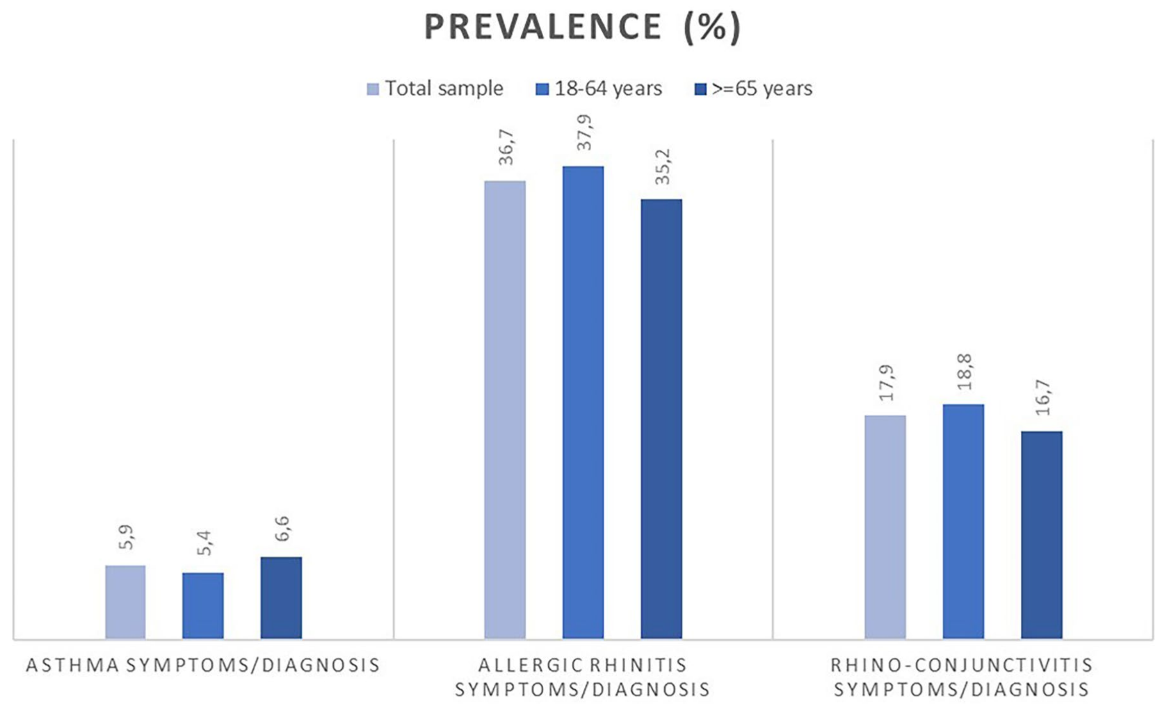


**Figure 1.** Prevalence of asthma and allergic conditions in the total population sample and by age group (%).

**Table 2.** Correlation matrix between annual mean concentrations of $NO_2$ (at 200 m and 1 km spatial resolution) and noise pollution (Lden).

| | $NO_2$ (200 m) (μg/m$^3$) | $NO_2$ (1 km) (μg/m$^3$) | Lden [dB(A)] |
|---|---|---|---|
| $NO_2$ (200 m) (μg/m$^3$) | 1 | **0.449** | **0.261** |
| $NO_2$ (1 km) (μg/m$^3$) | **0.449** | 1 | −0.033 |
| Lden [dB(A)] | **0.261** | −0.033 | 1 |

$NO_2$: nitrogen dioxide; Lden: day-evening-night noise level as described in the text; dB(A): A-weighted decibels, an expression of the relative loudness of sounds in air as perceived by human ears.
In bold the statistically significant correlations ($p$-value ≤ 0.050).

exposed to higher levels of $NO_2$ and noise, except for $NO_2$ at 1 km resolution (Table 3).

The probabilities of having asthma/allergic symptoms/diagnosis in adult (18–64 years) subjects and the elderly (≥65 years) exposed to traffic are reported in Tables 4a and 4b.

No significant associations emerged in adult subjects (Table 4a). Conversely, elderly subjects reporting vehicular traffic exposure and being exposed to high noise levels [Lden ≥ 60 dB(A)] showed significantly higher odds of allergic rhinitis symptoms/diagnosis (OR 2.01, 95% CI 1.09–3.70, and OR 1.99, 95% CI 1.18–3.36, respectively), as well as, at a borderline significance level, higher odds of rhino-conjunctivitis symptoms/diagnosis (OR 2.20, 95% CI 0.95–5.10, and OR 1.76, 95% CI 0.91–3.42, respectively) than the elderly not exposed to traffic. No significant effect for modelled $NO_2$ exposure was found (Table 4b).

**Table 3.** Comparisons between traffic exposure assessed by questionnaire and objective measures of air and noise pollution.

| | Traffic exposure—*Q* | | |
|---|---|---|---|
| | Exposed | Not exposed | *p*-Value |
| $NO_2$ (200 m) (μg/m$^3$) (mean ± *SD*) | 28.52 ± 3.29 | 27.75 ± 3.16 | **0.004** |
| $NO_2$ (1 km) (μg/m$^3$) (mean ± *SD*) | 27.31 ± 2.81 | 27.08 ± 3.68 | 0.369 |
| Lden [dB(A)] (mean ± *SD*) | 59.23 ± 6.02 | 55.07 ± 6.06 | **<0.001** |
| Noise exposure (%) | | | |
| ≥60 dB(A) | 52.2 | 18.7 | **<0.001** |
| <60 dB(A) | 47.8 | 81.3 | |

*SD*: standard deviation; *Q*: through questionnaire; $NO_2$: nitrogen dioxide; Lden: day-evening-night noise level as described in the text; dB(A): A-weighted decibels, an expression of the relative loudness of sounds in air as perceived by human ears.
In bold the statistically significant values ($p$-value ≤ 0.050).

## Discussion

We found that ≥65 years subjects showed higher odds of allergic rhinitis and rhino-conjunctivitis symptoms/diagnosis if exposed to vehicular traffic (reported by questionnaire) and to high Lden noise levels [≥60 dB(A)]. No significant association was found in adults (18–64 years) or with $NO_2$ exposure.

Being the prevalence of allergic diseases particularly elevated among subjects under 18 years of age, most studies on this topic were conducted in this age group. Indeed, the period between prenatal to childhood was acknowledged as critical time window during which exposure to air pollution can significantly impact the

**Table 4a.** Associations (OR and 95% CI) between traffic-related exposure and asthma/allergic symptoms/diseases in subjects aged 18–64 years ($n = 372$).

| | Traffic exposure—*Q* | Lden ≥60 dB(A) | $NO_2$ (200 m) (μg/m³)* | $NO_2$ (1 km) (μg/m³)* |
|---|---|---|---|---|
| | OR (95% CI) | OR (95% CI) | OR (95% CI) | OR (95% CI) |
| Outcome | | | | |
| Asthma symptoms/diagnosis | 0.71 (0.29–1.79) | 0.91 (0.35–2.37) | 1.09 (0.95–1.25) | 0.98 (0.86–1.13) |
| Allergic rhinitis symptoms/diagnosis | 1.11 (0.72–1.72) | 1.25 (0.80–1.94) | 0.98 (0.92–1.05) | 1.06 (0.99–1.13) |
| Rhino-conjunctivitis symptoms/diagnosis | 0.98 (0.56–1.69) | 0.82 (0.47–1.44) | 0.97 (0.89–1.06) | 1.05 (0.96–1.14) |

OR: odds ratio; CI: confidence interval; *Q*: through questionnaire; Lden: day-evening-night noise level as described in the text; dB(A): A-weighted decibels, an expression of the relative loudness of sounds in air as perceived by human ears; $NO_2$: nitrogen dioxide.
Logistic regression models adjusted for: sex, educational level, occupational exposure, and smoking habits.
*Per 1 μg/m³ increases.

**Table 4b.** Associations (OR and 95% CI) between traffic-related exposure and asthma/allergic symptoms/diseases in subjects aged ≥65 years ($n = 273$).

| | Traffic exposure—*Q* | Lden ≥60 dB(A) | $NO_2$ (200 m) (μg/m³)* | $NO_2$ (1 km) (μg/m³)* |
|---|---|---|---|---|
| | OR (95% CI) | OR (95% CI) | OR (95% CI) | OR (95% CI) |
| Outcome | | | | |
| Asthma symptoms/diagnosis | 2.43 (0.64–9.22) | 0.78 (0.28–2.14) | 0.92 (0.79–1.07) | 0.90 (0.78–1.04) |
| Allergic rhinitis symptoms/diagnosis | **2.01 (1.09–3.70)** | **1.99 (1.18–3.36)** | 0.99 (0.92–1.07) | 0.97 (0.89–1.06) |
| Rhino-conjunctivitis symptoms/diagnosis | ***2.20 (0.95–5.10)*** | ***1.76 (0.91–3.42)*** | 1.00 (0.91–1.10) | 0.98 (0.88–1.09) |

OR: odds ratio; CI: confidence interval; *Q*: through questionnaire; Lden: day-evening-night noise level as described in the text; dB(A): A-weighted decibels, an expression of the relative loudness of sounds in air as perceived by human ears; $NO_2$: nitrogen dioxide.
Logistic regression models adjusted for: sex, educational level, occupational exposure, smoking habits.
In bold: statistically significant values ($p$-value ≤ 0.050); in bold italic: borderline value ($0.050 < p$-value $< 0.100$).
*Per 1 μg/m³ increases.

later development of allergies and asthma [37–39]. However, these conditions often persist into older age and can even begin in the elderly [20,40,41]. The vulnerability and susceptibility associated with ageing may lead to a higher impact of air pollution exposure on respiratory health in elderly subjects [9,11].

Ageing is associated with a decline in immune defences and respiratory function, an increase in comorbidities, and in a predisposition to respiratory infections, which may trigger allergies or asthma exacerbation, as well as asthma later onset [9,11,20,40,41].

The elderly tend to spend more time at home and to be more exposed to traffic near their residence. Furthermore, with respect to the elderly, younger subjects of working age may be less exposed to traffic pollution close to their residence due to different time-activity patterns. Indeed, in our sample, the elderly reported a significantly larger exposure to traffic and were more exposed to high levels of noise (i.e. Lden) than adult people (Table 1). Also, in our previous paper, we found that people spend the largest part of their daily lives indoors, especially at home, with the highest percentages in ≥65 years subjects (75% in winter and 66% in summer), with respect to 15–64 years subjects (65% in winter and 59% in summer) [42].

### *Traffic-related exposure by questionnaire*

We have found significant associations between traffic exposure reported by questionnaire and allergic rhinitis and rhino-conjunctivitis symptoms/diagnosis in the elderly.

These results are in line with those of our previous studies performed in Pisa, based on different proxy of traffic exposure such as: living near a major road (<100 m) and odds of atopy in females (OR 1.83, 95% CI 1.11–3.00) [43]; a 10% increase in grey spaces coverage near home and odds of allergic rhinitis (OR 1.10, 95% CI 1.04–1.17) and asthma/allergic rhinitis (OR 1.06, 95% CI 1.00–1.12) [44]; living in urban area *vs.* suburban area and odds of allergic rhinitis (OR 1.19, 95% CI 1.05–1.35) [26].

Another Italian study on adult subjects showed associations between asthma prevalence and self-reported high-traffic intensity (OR 1.46, 95% CI 1.05–2.03) and between rhinitis and different traffic-related indicators (self-reported high-traffic intensity, OR 1.30, 95% CI 1.05–1.62; living at a distance of 50–100 m from a main road, OR 1.26, 95% CI 1.03–1.54) [45]. A US study on adult subjects found a relationship between residence near main roads and both current allergies (OR 1.35, 95% CI 1.07–1.35) and current asthma (OR 1.51, 95% CI 1.14–2.00) [46]. In a Swedish study on adult subjects, associations between self-reported traffic exposure and both allergic asthma and allergic rhinitis were found (OR 1.32, 95% CI 1.05–1.66, and OR 1.13, 95% CI 1.01–1.26, respectively) [47].

With regard to asthma symptoms, international studies highlighted that living near busy roads was a risk factor for asthmatic symptoms in adults [48, 49] and elderly [50]; others didn't find significant associations [46,51].

Conversely, we didn't find significant associations with asthma symptoms/diagnosis, even if a likely relation emerged with traffic exposure assessed by questionnaire (OR 2.43). The absence of statistically significant results might be due to the small number of elderly subjects reporting asthma symptoms/diagnosis. Indeed, asthma is generally under-recognized and undertreated in older adults [40]. Alternatively, this result might depend on asthma subtypes (allergic and non-allergic). In fact, in Swedish adults, significant associations were found only for allergic asthma and allergic rhinitis, and not for non-allergic asthma and non-allergic rhinitis. Thus, traffic exposure might be related to allergic diseases, but not to asthma or rhinitis triggered by non-allergic factors in adults [47].

Air pollution can induce or aggravate symptoms of allergic conjunctivitis. A recent review showed a relationship between air pollution exposure and an increase in outpatient visits due to allergic conjunctivitis in subjects living in urban areas, as well as an increase in the prevalence of the disease [52]. Other authors suggested that rhino-conjunctival tissue is very sensitive to irritant stimuli during ongoing allergic inflammation and that susceptibility toward allergens might be increased in areas with increased levels of air pollutants [53].

### Noise level exposure

Significant associations between allergic and rhinoconjunctivitis' outcomes and traffic exposure were found using model-derived measures of traffic noise. There is literature evidence on the relationship between higher noise levels and psychophysics disorders, such as stress reactions, sleep disorders, cognitive impairment, but also endocrine imbalance, premature death, and cardiovascular diseases [2,54]. Road traffic noise, like air pollutants, may trigger defensive body responses inducing alterations in the immune system, systemic inflammation, and increasing oxidative stress, potentially resulting in respiratory exacerbations [55].

Despite this plausibility, only few studies investigated the role of traffic noise on respiratory health yielding inconsistent results. In three adult European cohorts, there was no association between traffic noise exposure and asthma prevalence in adults [16]. On the contrary, a study on 7000 Swiss adults showed associations among noise levels and asthma exacerbation [19]. Similar results were found in an Iranian adult sample highlighting the role of noise level during the daytime as a risk factor for asthma symptoms, but not for asthma diagnosis [56]. More recently, a novel finding of an association between road traffic noise and adult-asthma incidence was presented [17]. With regard to allergic diseases, a Korean study on about 2000 students found a relationship between the incidence of allergic diseases (asthma or allergic rhinitis or atopic dermatitis) and higher levels of night-time noise level [57].

Thus, we found new insights on the possible role of traffic noise on allergic symptoms/diseases in the elderly living in a city characterized by a mean daily road noise level (Lden: 58 dB(A)) somewhat above the high noise threshold defined in the EU Directive (55 dB(A)) and the WHO guidelines (53 dB(A)) [1,36].

### $NO_2$ modelled exposure

It is well known that $NO_2$ is an airway irritant gas and it may change the allergens' conformation or stability, thus increasing their allergenic potential [4,12,58]. In epidemiological studies, $NO_2$ is widely used as a marker of vehicular traffic and associations with wheezing, shortness of breath, and current atopic asthma have been found in middle-aged adults [59,60]. Data from three adult European cohorts showed that $NO_2$ (per 10 μg/m$^3$ increase) was associated with lifetime asthma prevalence (OR 1.02, 95% CI 1.01–1.03). This effect was slightly larger in those aged ≥50 years [16]. A recent Irish study on adult subjects (>50 years) found that a 1 ppb increase (about 2 μg/m$^3$) in local $NO_2$ was associated with a 0.15–0.25 percentage point increase in the probability of suffering from self-reported asthma [61]. A Chinese study on 40279 adults from eight cities found that a 10 μg/m$^3$ increase of $NO_2$ was related to having asthma with an OR of 1.24 (95% CI 1.09–1.42) and to having allergic rhinitis with an OR of 1.17 (95% CI 1.06–1.31) [62]. Another Italian study concerning adult subjects showed associations between $NO_2$ increase (10 μg/m$^3$) and rhinitis (OR 1.07, 95% CI 1.04–1.10) and asthma (OR 1.07, 95% CI 1.03–1.12) [24]. Other studies found no significant associations for $NO_2$ [51] or less consistent associations when compared with effects due to self-reported traffic exposure [47,63].

Our sample lived in an urban area characterized by $NO_2$ level (27–28 μg/m$^3$) below the current EU ambient air quality standards (40 μg/m$^3$), but above the new WHO recommendations (10 μg/m$^3$); nevertheless, we showed no association between the investigated health outcomes and $NO_2$ exposure. A possible explanation might be an insufficient spatial contrast in exposure (interquartile range: 5 μg/m$^3$ for $NO_2$ at 200 m and 2 μg/m$^3$ for $NO_2$ at 1 km) that didn't permit the detection of any health adverse effect.

### *Strengths and limitations*

Strengths of our study include its novelty in the concomitant investigation of the relationship of different proxies of traffic exposure (reported by questionnaire, Lden levels, and $NO_2$ concentration) with respiratory/allergic health in the elderly. In addition, our study points out the usefulness of using proxies obtained through different methods for better estimating the health effects of individual urban traffic exposure, in terms of chemical and physical air pollution. We used pollution data with high spatial resolution, estimated using advanced statistical methodologies (deterministic and machine learning methods), to assess exposure at the individual level, overcoming the problems related to spatial coverage and interpolation that occur when using only data from monitoring stations. In our study, noise exposure represented an added value that proved to be a good proxy of residential traffic pollution exposure, indirectly related to allergic outcomes. The noise measure is likely to be more related to elderly health status than that of $NO_2$ at 200 m or 1 km resolution, as it was estimated at building level (at the most exposed façade). Actually, the estimation of traffic noise seems to better reflect the exposure reported by questionnaire (Table 3).

The use of the questionnaire to collect information on respiratory symptoms/diseases might be a limitation, as based on individual memory and potentially influenced by personal perception of the health status and actual traffic exposure. Nevertheless, the standardized questionnaire is one of the best investigative tools in respiratory epidemiology [64].

Moreover, the information reported by elderly subjects may be more accurate than those reported by the adults, as the former spend more time at home and pay more attention to the frequency of cars' passage near home.

A study limitation concerns the use of air pollution data after (2013) the period of health data collection (2009–2011). At the same time, it has been hypothesized from previous studies that spatial contrasts in average pollutant exposure levels across areas (residential addresses) remain approximately constant over the years, regardless of the direction of the changes in average pollutant concentration. Therefore, it may be assumed that spatial changes in pollutant concentrations turn out to be more relevant for chronic exposure than temporal changes: the most exposed subjects remain most exposed even despite a decrease in pollutant concentrations over time [65]. Indeed, for the Pisa area, it has been demonstrated by Fasola et al. [22]. This assumption about the spatial stability of air pollution contrasts permitted the application of recently developed models for long-term exposure in previously enrolled cohorts, as made in other international studies [65]. On the other side, hopefully, new technologies providing finer temporal and spatial estimates of air pollutant exposure will allow to overcome gaps due to the temporal inconsistency in similar studies.

The low sample size of subjects living in an urban area, together with the low spatial variability in the $NO_2$ exposure levels, was an important limitation, possibly leading to less accurate estimations. Despite this issue, we provided new information about allergic diseases for one of the most vulnerable population categories, the elderly.

Another limitation is the lack of information on individual exposure linked to daily commuting, the indoor microenvironment, the diet, and any other factor that could potentially contribute to defining the 'total human exposure', together with the genetic predisposition to allergic diseases. Future studies could benefit from integrating various sources of exposure to provide a thorough overview of the effects of air pollution on the elderly health.

As the world population continues to age, the health consequences of traffic exposure, particularly on allergic diseases in the elderly, will become a major medical, social, and economic problem, with important consequences on the quality of life.

## Conclusions

In conclusion, we showed higher odds of allergic rhinitis and rhino-conjunctivitis in the elderly with chronic exposure to traffic-related air pollution and high noise levels.

These findings highlight the need to better assess the effect of air pollution in the elderly population and to increase awareness on allergic and asthmatic diseases within this age group. This is particularly crucial considering the increasing trend in the future global population's ageing.

Our study demonstrated that the urban population, even in a small-medium size town, is exposed to elevated levels of traffic pollution and noise, as already highlighted by the European Environment Agency. Consequently, intervention measures are imperative to mitigate the population's exposure. These measures should concentrate on addressing traffic sources and redesigning urban planning, such as changing traffic patterns and expanding green areas.

Moreover, a major effort is requested to define common European limits for noise pollution and to reconsider current European air quality legislation in order to prevent not only premature deaths but also the onset and exacerbation of respiratory/allergic chronic diseases.

## Authors contributions

ST, SM, SF, and SB were involved in the conception and design, analysis and interpretation of the data, the drafting of the paper, and revising it critically for intellectual content. GV was involved in the interpretation of the data and revising it critically for intellectual content. IS and GS were involved in the drafting of the paper and revising it critically for intellectual content. AM, CG, CS, FP, GL, and MS were involved in revising the paper critically for intellectual content. All authors have given their final approval of the version to be published. All authors agree to be accountable for all aspects of the work.

## Disclosure statement

No potential competing interest was reported by the author(s).

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## ORCID

Sofia Tagliaferro http://orcid.org/0000-0002-9602-970X

## Data availability statement

The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

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