

BMJ Open Are noise and air pollution related to the incidence of dementia? A cohort study in London, England

Iain M Carey,¹ H Ross Anderson,^{1,2} Richard W Atkinson,¹ Sean D Beevers,² Derek G Cook,¹ David P Strachan,¹ David Dajnak,² John Gulliver,³ Frank J Kelly^{2,4}

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¹Population Health Research Institute, St George's, University of London, London, UK

²MRC-PHE Centre for Environment and Health, King's College London, London, UK

³UK Small Area Health Statistics Unit, MRC-PHE Centre for Environment and Health, Imperial College, London, UK

⁴NIHR HealthProtection Research Unit in Health Impact of Environmental Hazards, King's College London, London, UK

Correspondence to

Dr Iain M Carey;
sgjd450@sgul.ac.uk

ABSTRACT

Objective To investigate whether the incidence of dementia is related to residential levels of air and noise pollution in London.

Design Retrospective cohort study using primary care data.

Setting 75 Greater London practices.

Participants 130 978 adults aged 50–79 years registered with their general practices on 1 January 2005, with no recorded history of dementia or care home residence.

Primary and secondary outcome measures A first recorded diagnosis of dementia and, where specified, subgroups of Alzheimer's disease and vascular dementia during 2005–2013. The average annual concentrations during 2004 of nitrogen dioxide (NO₂), particulate matter with a median aerodynamic diameter ≤2.5 μm (PM_{2.5}) and ozone (O₃) were estimated at 20×20 m resolution from dispersion models. Traffic intensity, distance from major road and night-time noise levels (L_{night}) were estimated at the postcode level. All exposure measures were linked anonymously to clinical data via residential postcode. HRs from Cox models were adjusted for age, sex, ethnicity, smoking and body mass index, with further adjustments explored for area deprivation and comorbidity.

Results 2181 subjects (1.7%) received an incident diagnosis of dementia (39% mentioning Alzheimer's disease, 29% vascular dementia). There was a positive exposure response relationship between dementia and all measures of air pollution except O₃, which was not readily explained by further adjustment. Adults living in areas with the highest fifth of NO₂ concentration (>41.5 μg/m³) versus the lowest fifth (<31.9 μg/m³) were at a higher risk of dementia (HR=1.40, 95% CI 1.12 to 1.74). Increases in dementia risk were also observed with PM_{2.5}, PM_{2.5} specifically from primary traffic sources only and L_{night}, but only NO₂ and PM_{2.5} remained statistically significant in multipollutant models. Associations were more consistent for Alzheimer's disease than vascular dementia.

Conclusions We have found evidence of a positive association between residential levels of air pollution across London and being diagnosed with dementia, which is unexplained by known confounding factors.

BACKGROUND

Dementia, encompassing both vascular dementia and Alzheimer's disease, is now reported as the leading cause of death in

Strengths and limitations of this study

- Annual concentrations during 2004 for air and noise pollution exposure were modelled at a fine resolution, including near-road estimates of traffic pollution.
- Pollution data were anonymously linked to electronic health records of over 100 000 older adults registered with 75 general practices in Greater London during 2005–2013.
- Incident dementia diagnoses were identified, including Alzheimer's disease and vascular dementia.
- The robustness of the results was tested for by adjusting for area deprivation and other comorbidities.
- Accuracy and completeness of primary care diagnoses of dementia and subdiagnoses are a known issue.

England and Wales, accounting for 12% of all registered deaths.¹ While temporal changes in recording may have influenced how the underlying cause is now determined, more important are increases in longevity among the population at older ages, caused by declining trends in deaths from cardiovascular and cerebrovascular disease.² In terms of years of life lost, the Global Burden of Disease in 2013 ranked all dementia as the fifth leading cause,² noting their increasing importance as a cause of death despite little change in age-standardised rates. Therefore, primary prevention of all dementia is a major global public health concern for the coming decades.³ For Alzheimer's disease for example, while it has been estimated that small delays in its onset and progression could significantly reduce its estimated future burden,⁴ research has primarily focused on lifestyle factors, where a large systematic review estimated that about a third of Alzheimer's disease may be attributable to potentially modifiable risk factors such as smoking and physical inactivity.⁵

More recently research has also extended to the role of environmental risk factors

and dementia, where a large systematic review identified moderate evidence for an association with eight different factors including air pollution.⁶ While air pollution is a well-established risk factor for cardiovascular and respiratory disease,⁷ its role in relation to dementia is less well considered and understood.⁸ A recent systematic review of the epidemiological evidence linking air pollution to dementia-related outcomes identified 18 studies, with most reporting adverse associations.⁹ However, there was a significant variation in the size and quality of the studies involved, reiterating the noted lack of robust longitudinal or population-based studies.^{6, 8} Subsequently, a large population-based study in Ontario, Canada, reported that living close to major roads was associated with a higher incidence of dementia,¹⁰ with a further analysis revealing corresponding associations with modelled levels of nitrogen dioxide (NO₂) and mass of fine particulate matter with a median aerodynamic diameter $\leq 2.5 \mu\text{m}$ (PM_{2.5}).¹¹ These findings raise questions around the mechanisms for the early development of neuroinflammation and neurodegeneration,¹² and require further exploration and replication in other large population cohorts with different exposure models, including traffic noise which has been linked to cognitive decline in adults.¹³

In this paper, we use modelled estimates at a fine spatial scale for modelled estimates of air and noise pollution to investigate relationships with the incidence of dementia across Greater London.

METHODS

Data source

The Clinical Practice Research Datalink (CPRD) is a large, validated primary care database that has been collecting anonymous patient data from participating UK general practices since 1987.¹⁴ It has been shown to be broadly representative of the UK population, with about 7% of all people in the UK actively registered on it in 2011.¹⁴ Approximately three-quarters of contributing CPRD practices in England have consented to their data being linked to external sources. This is facilitated by a 'trusted third party' to CPRD, ensuring that researchers have no access to geographical identifiers such as residential postcode. Key variables which have been linked to the practice data include the Index of Multiple Deprivation (IMD), a composite small-area (approximately 1500 people) measure used in England for allocation of resources,¹⁵ and the Office for National Statistics death registration data, which allows underlying cause of death to be identified. For this study, we selected 75 (linked) practices that lay within the study area bounded geographically by the orbital M25 motorway around Greater London (60 were in outer London boroughs, 15 were in inner London boroughs) that were continually recording data between 2004 and 2010.¹⁶

Estimates of air and noise pollution exposure

The following measures of exposure, estimated annually between 2004 and 2010, were linked to CPRD: (1) air pollution concentrations, (2) traffic intensity or distance measures, and (3) road traffic noise levels. A priori we chose to focus on annual concentrations estimated in 2004 as this was the earliest year linked. Modelled estimates in other years (2005–2010) were highly correlated ($r > 0.95$), and repeating the analysis using alternative years produced identical results (data not shown).

Modelled annual concentrations for air pollutants were estimated using the KCLurban dispersion modelling system at a resolution of 20×20 m.¹⁷ It incorporates hourly meteorological measurements, empirically derived concentrations of NO-NO₂-O₃ and derived PM (particulate matter), using information on source emissions from the London Atmospheric Emissions Inventory.¹⁸ For this analysis, we focused on annual concentrations in 2004 for NO₂, PM_{2.5} (fine particulate matter with a median aerodynamic diameter $\leq 2.5 \mu\text{m}$) and O₃ (ozone). Additionally, we present an estimate for primary PM_{2.5} attributable to road traffic sources estimated from the sum of contributions from the following emission sources: tyre, brake, exhaust, surface wear and resuspension.¹⁷ Air pollution concentration estimates were derived for each of the 190 115 London postcodes address centroids based on interpolation from the closest 20×20 m point of the dispersion model.¹⁸ This resulted in patients residing in the same postcodes, which typically average about 15 households nationally, being assigned the same exposure levels. Additionally, some postcodes covering smaller geographical areas may also be assigned to the same 20×20 m point. The exposure concentrations were linked to CPRD by the 'trusted third party', who subsequently remove the postcode, ensuring we had no direct access to any geographical identifiers.

Traffic proximity measures were developed relating to 'heavy' vehicle density, which was defined as light goods vehicles, heavy goods vehicles (rigid and articulated trucks/lorries), buses and coaches. We included a distance measure (in metres) from the postcode centroid to the nearest road classified in the top quartile of heavy vehicle intensity. Traffic intensity was estimated as total vehicle kilometre driven (heavy vehicles only) in each year for all major roads that fell within a 50 m and 50–100 m radius of the postcode address centroid. We used an arbitrary cut-off of >100 000 km driven to define 'high volume' in the analyses.

Road traffic noise levels were estimated using the TRANEX model.¹⁹ This uses information on road traffic flows and speeds, road geography, land cover, and building heights to estimate average sound pressure level (LA_{eq}) in decibels (dB) over different time periods. Evaluations of TRANEX in two other English cities have shown high correlation ($r \geq 0.85$) between modelled and measured 1-hour LA_{eq}.¹⁹ In our analysis, we focused on the average annual L_{night} recorded overnight between 23:00 and 07:00, as this period

represents when most of our study subjects would be at their residence. Alternative analyses using daytime noise (LA_{eq16}) produced identical results (data not shown) due to the extremely high correlation with night noise ($r=0.999$).²⁰ For the linkage of the noise model to CPRD, the geometric centroids of the address locations in each postcode were directly used.

Cohort definition

Among the 75 practices, a total of 555 385 patients were actively registered on 1 January 2005, representing about 7% of the Greater London population at that time. From these, we selected 139 718 adults aged 50–79 years who had been registered for ≥ 1 year continuously with their practice. From this group, 131 869 (94%) were successfully linked to our pollution exposures. Non-linkage was mainly due to a few practices being near the study area boundary, so many of their patients' individual postcodes were not eligible. Patients were followed until the earliest of (1) date of first diagnosis of dementia, (2) date of death or deregistration from practice, (3) date when the practice ceased contributing to CPRD and (4) 31 December 2013.

We searched the primary care records for the date of first dementia diagnosis, using the Read codes for dementia within the Quality and Outcomes Framework (QOF).²¹ Although most Read codes are non-specific, we identified subgroups that classified the dementia as Alzheimer's disease or vascular dementia. Using the death records, we also used the International Classification of Diseases 10th Revision codes to identify patients with dementia listed as the primary cause of death (if not coded as such on the general practitioner (GP) record), and to further classify them based on specific mention of Alzheimer's disease or vascular dementia anywhere on the death record. We also extracted from the GP record information on ethnicity, smoking, body mass index (BMI) and alcohol consumption, using the last measurement before baseline when available, or during the study if that was the only one available. A missing category was retained where no information was available. In addition, we extracted information on comorbidity recorded at baseline, based on a list of conditions we have previously shown to be independently predictive of mortality.²²

Patients ($n=391$) with an existing diagnosis of dementia by 1 January 2005 were excluded. Additionally, we sought to exclude patients ($n=423$) when there was evidence on their medical record that they were living in a residential or care home as of 1 January 2005. We did this through a combination of Read codes, or where four or more patients aged 65–99 were recorded living at the same address. We also excluded a small number of patients ($n=77$) where no IMD could be assigned. This resulted in 130 978 eligible patients for our analyses.

Statistical analyses

We used Cox proportional hazards models to investigate the associations between all exposure measures

estimated in the year before baseline (2004) and subsequent dementia incidence. To account for the clustering by practice (homogeneity between patients from the same practice), we fitted models with a shared frailty (at practice level), which are the survival data equivalent to random effects.²³ We adjusted cumulatively for (1) age, sex, ethnicity, smoking and BMI (recorded alcohol consumption was not independently predictive and was dropped from the model), (2) IMD decile (based on national ranking across England) and (3) comorbidities (ischaemic heart disease (IHD), stroke, heart failure, diabetes) that were independently predictive of dementia. For model (2) we explored the effect of adjusting for other pollutants (air pollution for noise and vice versa). In sensitivity analyses, we explored within-practice and between-practice effects by fitting different models (a non-frailty model stratified on practice, practice fitted as a fixed effect, fitting practice mean exposure level in addition to individual level). For all pollutants, we fitted a continuous measure based on IQR to enable comparison between estimates, and quintiles to describe the shape of the association. All analyses were carried out in Stata V.13.

Patient and public involvement

No patients were involved in developing the research question, outcome measures and overall design of the study. Due to patient anonymity, we are unable to disseminate the results of the research directly to study participants.

RESULTS

During the study follow-up period (mean=6.9 years), a total of 2181 patients (1.7%, incidence rate 2.4 per 1000 per year) received a first diagnosis of dementia during follow-up (table 1). Among those patients diagnosed, 848 (38.9%) had a mention of Alzheimer's disease, 634 (29.1%) mentioned vascular dementia, while 747 (34.3%) received a non-specific Read code. A total of 48 patients (2.2%) received diagnoses for both Alzheimer's disease and vascular dementia. While crude incidence rates for dementia were lowest in smokers, later adjustment for age and other covariates explained this association; however, the lowest dementia risk seen in obese subjects persisted (data not shown).

The summary statistics for the modelled air and noise pollutants in 2004 are shown in table 2. All air pollutants were strongly positively related to each other ($r>0.9$), except for O_3 which was negatively correlated ($r=-0.9$ or greater) with both NO_2 and $PM_{2.5}$. Night noise (L_{night}) was positively related to NO_2 and $PM_{2.5}$, but associations were less in magnitude ($r=0.3-0.4$) to all air pollutants. A different pattern for noise was also observed when intraclass correlations (ICCs) were calculated by practice. While most variation by noise was observed within practices (ICC=0.05), the opposite was true for air pollutants where most variation was between practice (ICC>0.7). When mean concentrations were calculated by traffic distance and intensity (online supplementary table S1),

Table 1 Incidence rates of dementia during follow-up by characteristics of eligible subjects estimated at baseline

Baseline variable	Grouping	First diagnosis of dementia 2005–2013†									
		All subjects		Any		Alzheimer's disease		Vascular		Non-specific	
		n	%	n	IR*	n	IR*	n	IR*	n	IR*
	All	130978	100	2181	2.40	848	0.93	634	0.69	747	0.82
Sex	Men	65130	49.7	948	2.14	326	0.73	301	0.68	344	0.78
	Women	65848	50.3	1233	2.63	522	1.11	333	0.71	403	0.86
Age	50–59	59587	45.5	99	0.23	38	0.09	17	0.04	45	0.11
	60–69	41013	31.3	427	1.49	175	0.61	102	0.36	155	0.54
	70–79	30378	23.2	1655	8.27	635	3.14	515	2.54	547	2.70
Ethnicity	White	86896	66.3	1791	2.84	703	1.11	524	0.83	607	0.96
	Asian	7309	5.6	98	1.77	35	0.63	39	0.70	27	0.49
	Black	4287	3.3	101	3.29	32	1.04	32	1.04	37	1.20
	Unknown	32486	24.8	191	0.98	78	0.40	39	0.20	76	0.39
Smoking	Never	63478	48.5	1108	2.42	473	1.03	293	0.64	362	0.79
	Ex	33063	25.2	715	3.10	264	1.14	235	1.01	235	1.01
	Current	25733	19.7	308	1.76	95	0.54	89	0.51	133	0.76
	Missing	8704	6.7	50	1.09	16	0.35	17	0.37	17	0.37
BMI	<20	5188	4.0	173	5.09	66	1.93	52	1.52	58	1.69
	20–25	35642	27.2	702	2.81	276	1.10	201	0.80	237	0.94
	25–30	41281	31.5	721	2.44	304	1.02	202	0.68	238	0.80
	30+	25783	19.7	364	1.97	116	0.63	129	0.70	125	0.68
	Missing	23084	17.6	221	1.51	86	0.59	50	0.34	89	0.61
IHD	Yes	9928	7.6	342	5.21	91	1.38	141	2.14	117	1.77
	No	121050	92.4	1839	2.18	757	0.89	493	0.58	630	0.74
Stroke	Yes	3647	2.8	190	8.38	40	1.74	99	4.33	57	2.49
	No	127331	97.2	1991	2.24	808	0.91	535	0.60	690	0.77
Diabetes	Yes	10160	7.8	300	4.34	85	1.22	114	1.64	109	1.57
	No	120818	92.2	1881	2.24	763	0.90	520	0.62	638	0.76
Heart failure	Yes	1704	1.3	62	6.76	9	0.97	26	2.81	27	2.92
	No	129274	98.7	2119	2.35	839	0.93	608	0.67	720	0.80
IMD‡	1 (least)	26149	20.0	426	2.21	163	0.84	132	0.68	144	0.75
	2	31452	24.0	535	2.36	212	0.93	146	0.64	188	0.83
	3	26093	19.9	401	2.29	179	1.02	112	0.64	119	0.68
	4	30817	23.5	514	2.49	187	0.90	160	0.77	176	0.85
	5 (most)	16467	12.6	305	2.78	107	0.97	84	0.76	120	1.09
Borough	Inner	23111	17.6	390	2.51	123	0.79	134	0.86	143	0.92
	Outer	107867	82.4	1791	2.37	725	0.96	500	0.66	604	0.80
Registration length (years)	<10	40386	30.8	638	2.41	251	0.94	196	0.74	210	0.79
	10+	90592	69.2	1543	2.39	597	0.92	438	0.68	537	0.83

*Incidence rate per 1000 patients per year.

†n=48 patients appear in both Alzheimer's disease and vascular dementia categories.

‡These groups correspond to the fifths of the IMD ranking across England; thus, Greater London is under-represented in the most deprived fifth.

BMI, body mass index; IHD, ischaemic heart disease; IMD, Index of Multiple Deprivation.

Table 2 Summary statistics for the annual concentrations in 2004 of air (NO₂, PM_{2.5}, PM_{2.5} traffic, O₃) and noise (L_{night}) pollutants

Summary statistics		NO ₂ (µg/m ³)	PM _{2.5} (µg/m ³)	PM _{2.5} (traffic) (µg/m ³)	O ₃ (µg/m ³)	L _{night} (dB)
Mean±SD		37.1±5.7	15.7±0.8	1.4±0.5	38.0±3.9	52.1±4.6
Median (IQR)		36.4 (32.9–40.4)	15.6 (15.2–16.1)	1.3 (1.1–1.7)	38.2 (35.5–41.0)	49.9 (49.4–52.1)
Correlation coefficients	NO ₂	–	0.98	0.94	–0.99	0.33
	PM _{2.5}	0.98	–	0.97	–0.96	0.39
	PM _{2.5} (traffic)	0.94	0.97	–	–0.90	0.51
	O ₃	–0.99	–0.96	–0.90	–	–0.27
	L _{night}	0.33	0.39	0.51	–0.27	–
	ICC (practice)*	0.87	0.83	0.68	0.92	0.05

*Intraclass coefficient calculated across practice clusters.

L_{night}, night-time noise levels; NO₂, nitrogen dioxide; O₃, ozone; PM_{2.5}, particulate matter ≤2.5 µm.

all pollutants declined with increasing distance from major roads, except O₃ which was higher with further distance. While patients residing in postcodes closest to major roads (0–50 m) had much higher night noise levels than those farthest away (60.4 dB vs 50.9 dB), the difference in modelled air pollution concentrations, especially PM_{2.5}, was much less.

Table 3 summarises a series of adjusted HRs for an incident diagnosis of dementia associated with comparable interquartile changes in different pollutant exposures. The strongest positive associations were seen for NO₂, where a +7.5 µg/m³ change produced an HR of 1.16 (95% CI 1.05 to 1.28), adjusting for IMD and other confounders (HR2 in table 3). Further adjustment for related comorbidities (HR3=1.16) did not explain this association. Corresponding associations were smaller with other measures (PM_{2.5} HR=1.07, PM_{2.5} traffic HR=1.08, L_{night} HR=1.02, distance from road HR=1.02) or negative (O₃ HR=0.84). We explored different approaches in estimating within-practice and between-practice estimates (online supplementary table S2). For NO₂ and PM_{2.5} the HRs were >1 for both estimates, but the CIs were wide. For night noise (L_{night}), there was stronger evidence

suggesting between-practice association (HR=1.42, 95% CI 1.03 to 1.96). To investigate the shape of the association, figure 1 plots the adjusted HR (HR3 in table 3) by air and noise pollution fifths, and road distance and traffic intensity 50 m categories. The corresponding HRs are given in full in online supplementary table S3. For NO₂ and PM_{2.5} the increase in dementia risk was noticeably higher in the top fifth of exposure. Patients with an assigned annual exposure of NO₂ of >41.5 µg/m³ had a marked increase in risk (HR=1.40, 95% CI 1.12 to 1.74) compared with those in the bottom fifth (<31.9 µg/m³). For other measures (noise, distance, intensity), there was less evidence of any trend, while for O₃ the risk was highest in the lowest fifth of exposure (<34.7 µg/m³).

The associations between dementia and an interquartile change (+7.5 µg/m³) in NO₂ are explored further in figure 2, which plots the adjusted HRs (HR2 in table 3) from Cox models stratified on a series of risk factors. Generally, there was little evidence of any effect modification across these factors, with all categories producing an HR >1. Associations between NO₂ and dementia were still observed when restricted to patients registered for their practice continually for more than 10 years (HR=1.13,

Table 3 Adjusted HRs for incident dementia during 2005–2013 by air and noise pollutants

Exposure	IQR change	HR1* (95% CI)	HR2† (95% CI)	HR3‡ (95% CI)	HR4§ (95% CI)
NO ₂	+7.47 µg/m ³	1.17 (1.06 to 1.28)	1.16 (1.05 to 1.28)	1.16 (1.05 to 1.27)	1.15 (1.04 to 1.28)
PM _{2.5}	+0.95 µg/m ³	1.07 (1.02 to 1.12)	1.07 (1.02 to 1.12)	1.06 (1.02 to 1.12)	1.06 (1.01 to 1.13)
PM _{2.5} (traffic)	+0.58 µg/m ³	1.09 (1.02 to 1.17)	1.08 (1.01 to 1.16)	1.08 (1.01 to 1.16)	1.08 (0.99 to 1.18)
O ₃	+5.56 µg/m ³	0.84 (0.75 to 0.93)	0.84 (0.75 to 0.94)	0.85 (0.76 to 0.94)	0.85 (0.76 to 0.96)
L _{night}	+2.68 dB	1.02 (1.00 to 1.05)	1.02 (1.00 to 1.05)	1.02 (1.00 to 1.05)	1.01 (0.98 to 1.03)
Distance to major road	–310 m	1.02 (0.97 to 1.08)	1.02 (0.97 to 1.08)	1.02 (0.97 to 1.08)	1.00 (0.95 to 1.05)

*HR1: Cox model with practice fitted as shared frailty. Adjusted for age, sex, ethnicity, smoking and body mass index.

†HR2: As HR1, plus additional adjustment for Index of Multiple Deprivation.

‡HR3: As HR2, plus additional adjustment for comorbidity (ischaemic heart disease, stroke, diabetes, heart failure).

§HR4: As HR2, plus additional adjustment for L_{night} (NO₂ and PM_{2.5} estimates) or NO₂ (L_{night} and distance estimates).

L_{night}, night-time noise levels; NO₂, nitrogen dioxide; O₃, ozone; PM_{2.5}, particulate matter ≤2.5 µm.

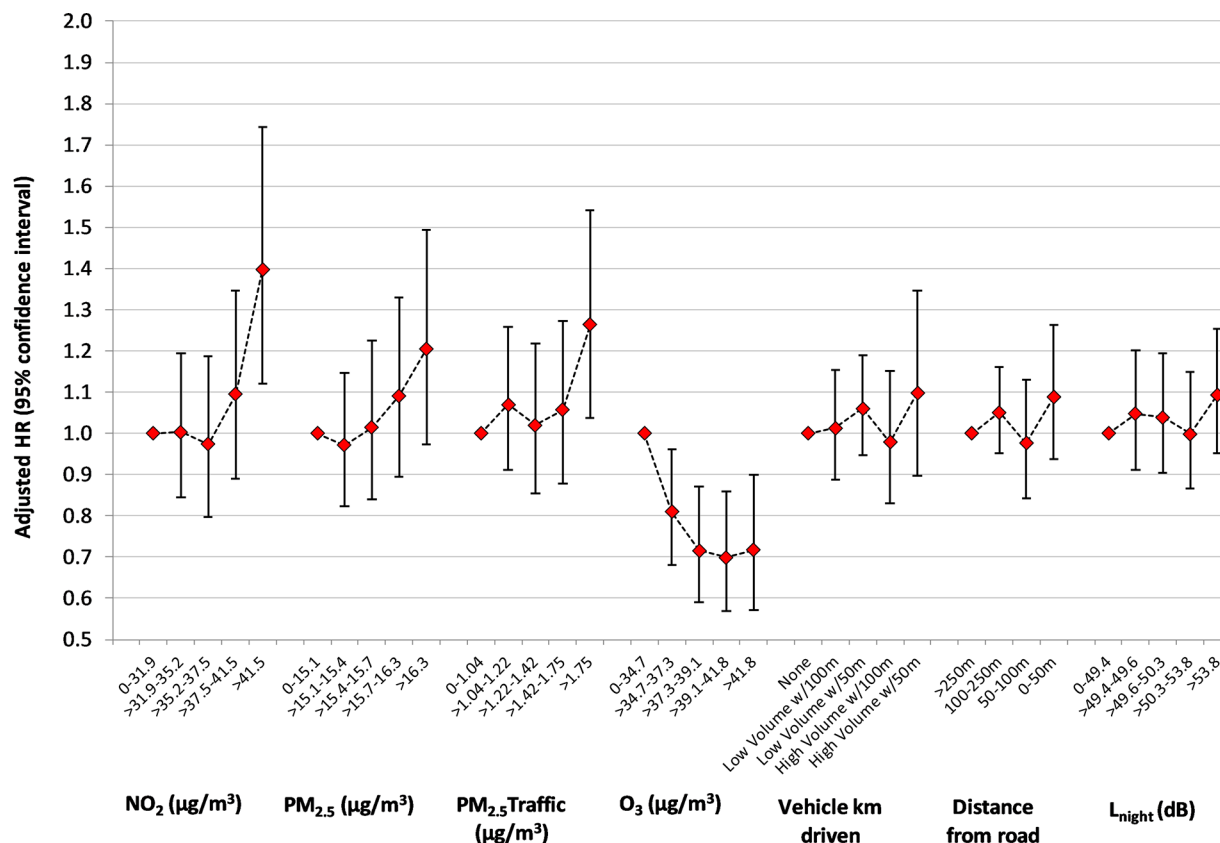


Figure 1 Adjusted HRs for all incident dementia during 2005–2013 by air and noise pollution fifths and traffic distance and intensity categories. HRs estimated from the Cox model with practice fitted as shared frailty. Adjusted for age, sex, ethnicity, smoking, body mass index and Index of Multiple Deprivation. HRs are given in full in online supplementary table S3. L_{night}, night-time noise levels; NO₂, nitrogen dioxide; O₃, ozone; PM_{2.5}, particulate matter ≤2.5 µm.

95% CI 1.01 to 1.26), or to patients without IHD, stroke, diabetes or heart failure at baseline (HR=1.21, 95% CI 1.08 to 1.34).

We repeated the analysis, now subclassifying dementia diagnoses recorded as Alzheimer's disease, vascular dementia or non-specific where no further information was available (table 4). The positive associations with NO₂ and PM_{2.5} were more consistent for Alzheimer's disease and non-specific diagnoses. For example, patients in the top fifth exposure category of NO₂ (>41.5 µg/m³) were at a higher risk of receiving an Alzheimer's disease diagnosis than patients in the bottom fifth (HR=1.50, 95% CI 1.08 to 2.08). For vascular dementia, there was less evidence of consistent effects with air or noise pollution.

DISCUSSION

In a sample of 75 general practices across Greater London, the recording of new dementia diagnoses was positively associated with measures of NO₂ and PM_{2.5} assigned at residential address at the beginning of the incident period. The association could not be explained by confounding and was consistent within subgroups. When we restricted to specific diagnoses, associations were still observed with Alzheimer's disease but not vascular dementia.

Strengths and weaknesses

While we were able to link pollution exposures to the primary care record to obtain diagnoses of dementia, there are concerns around the variability of dementia diagnoses in UK primary care,²⁴ and a recent review has concluded that dementia diagnoses on primary care databases may not be an accurate reflection of the true prevalence.²⁵ Under-recording is thought to be a common issue, as the diagnosis is associated with a stigma for many, and GPs may be reluctant to diagnose dementia unless highly certain.²⁶ A recent study across 23 London practices increased the prevalence on their QOF dementia registers by 9% by a simple coding review.²⁶ To account for under-recording at baseline, a priori we decided to exclude all patients identified as living in care homes at the beginning of follow-up regardless of dementia diagnosis. During follow-up, we observed broadly similar number of dementia subtypes being newly diagnosed, and since it is expected that about two-thirds of dementia is Alzheimer's disease,²⁷ this suggests the under-recording of Alzheimer's disease in particular may be an issue. Under-recording in our study could be problematic if it was related to key practice characteristics such as deprivation, as dementia recording has been shown to be lower among more affluent practices.^{24 28} In our

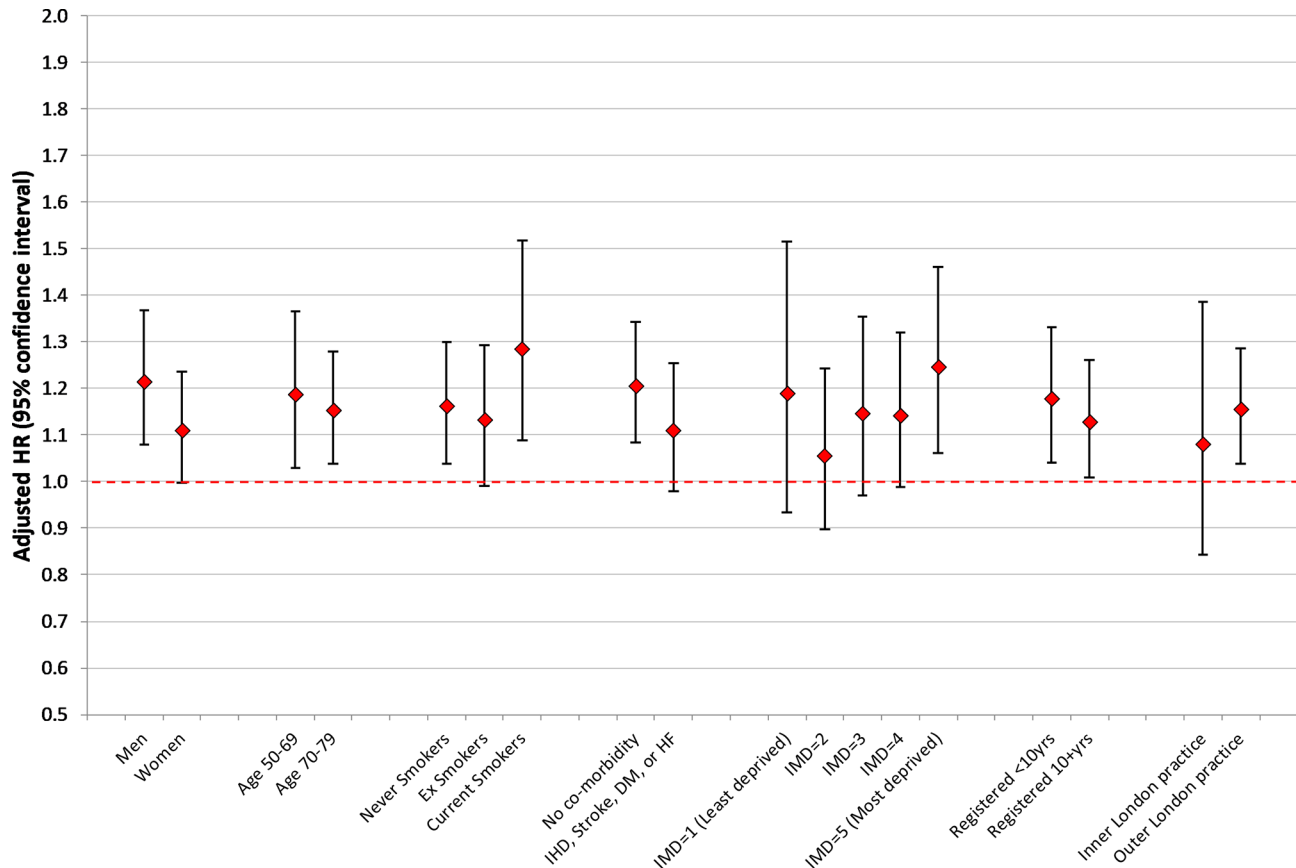


Figure 2 Stratified adjusted HRs for an interquartile increase ($7.5 \mu\text{g}/\text{m}^3$) in NO_2 and all incident dementia during 2005–2013. HRs estimated from Cox model with practice fitted as shared frailty. Adjusted for age, sex, ethnicity, smoking, body mass index and IMD. P values for interaction tests: age ($p=0.75$), sex ($p=0.27$), smoking ($p=0.47$), comorbidity ($p=0.31$), IMD ($p=0.72$), registration length ($p=0.62$) and practice borough ($p=0.63$). DM, diabetes mellitus; HF, heart failure; IHD, ischaemic heart disease; IMD, Index of Multiple Deprivation; NO_2 , nitrogen dioxide.

study we observed a wide range of incident rates by practice (0.2%–8.4%), and since the majority of air pollution variation was between practices we cannot discount unmeasured practice characteristics as a possible explanation for our findings. There are also known variations in the prevalence and diagnosis rates of dementia across England,²⁴ with London being among the reported lowest,²⁹ so we also have to acknowledge that the associations we observed may be specific within London and may not extend nationally.

Another weakness of the study is the lack of historical data surrounding exposure. Most large epidemiological studies of long-term exposure to pollution will have difficulty capturing an accurate picture of lifetime or cumulative exposure. This may be pertinent for Alzheimer's disease where the pathogenesis of the disease may take place over many years.³⁰ We did not have any information relating to previous address or location, and the London population is thought to be mobile and dynamic over time.³¹ Thus, we are making an assumption that an annual estimate for a single year (2004) represents long-term exposure, based on the last known address for the patient at that practice. We tested this in two ways: (1) sensitivity analyses based on patients who had been continually registered at their practice

for a long time (>10 years) produced similar findings; (2) where we did have other modelled years available during follow-up (2005–2010), these were highly correlated over time ($r>0.95$), so alternative analyses using them made no discernible difference. However, we cannot discount historical factors as an explanation for our findings. For example, it could be that recent exposure levels are acting as a proxy for other historical environmental factors linked to pollution, such as lead from petrol,³² where cumulative exposure has been linked to cognitive decline in later life.³³

A novel aspect of our analysis was the ability to simultaneously study the modelled effects of air and noise pollution on dementia, overcoming acknowledged limitations from other studies.^{11 34} Previous validation of the pollution models used in this study had shown low roadside correlation between them, suggesting that the independent effects of traffic pollution and road noise can be investigated.²⁰ However, a potential limitation is that by being based within Greater London, our air pollution exposure estimates may be somewhat homogeneous, lacking the variability we would expect to see nationally when more rural geographical areas are included. Within London, the contribution of regional (background) $\text{PM}_{2.5}$ and O_3 to overall levels

Table 4 HRs for incident Alzheimer's disease, vascular and non-specific dementia during 2005–2013 by air and noise pollutants

Exposure	Category (or IQR change)	Alzheimer's disease	Vascular dementia	Non-specific
		HR2* (95% CI)	HR2* (95% CI)	HR2* (95% CI)
NO ₂ (µg/m ³)	0–31.9	1 (reference)	1 (reference)	1 (reference)
	>31.9–35.2	0.98 (0.74 to 1.28)	0.94 (0.69 to 1.29)	1.09 (0.84 to 1.40)
	>35.2–37.5	0.99 (0.73 to 1.35)	0.83 (0.57 to 1.20)	1.08 (0.82 to 1.43)
	>37.5–41.5	1.15 (0.84 to 1.58)	0.98 (0.66 to 1.44)	1.01 (0.75 to 1.35)
	>41.5	1.50 (1.08 to 2.08)	1.01 (0.66 to 1.55)	1.55 (1.16 to 2.07)
	+7.5 (IQR change)	1.23 (1.07 to 1.43)	1.15 (0.96 to 1.39)	1.13 (0.99 to 1.28)
PM _{2.5} (µg/m ³)	0–15.1	1 (reference)	1 (reference)	1 (reference)
	>15.1–15.4	1.01 (0.77 to 1.32)	0.89 (0.66 to 1.20)	1.00 (0.77 to 1.28)
	>15.4–15.7	1.13 (0.84 to 1.52)	0.72 (0.50 to 1.02)	1.13 (0.86 to 1.47)
	>15.7–16.3	1.24 (0.92 to 1.68)	0.91 (0.63 to 1.32)	1.00 (0.76 to 1.33)
	>16.3	1.42 (1.03 to 1.96)	0.86 (0.57 to 1.30)	1.33 (0.99 to 1.77)
	+0.9 (IQR change)	1.10 (1.02 to 1.18)	1.06 (0.97 to 1.16)	1.06 (0.99 to 1.13)
PM _{2.5} traffic (µg/m ³)	0–1.04	1 (reference)	1 (reference)	1 (reference)
	>1.04–1.22	1.00 (0.76 to 1.30)	1.14 (0.86 to 1.52)	1.07 (0.84 to 1.38)
	>1.22–1.42	1.09 (0.82 to 1.45)	0.92 (0.66 to 1.27)	1.06 (0.81 to 1.38)
	>1.42–1.75	1.23 (0.93 to 1.64)	0.90 (0.63 to 1.28)	0.97 (0.73 to 1.27)
	>1.75	1.46 (1.08 to 1.98)	0.99 (0.68 to 1.44)	1.33 (1.00 to 1.75)
	+0.58 (IQR change)	1.13 (1.02 to 1.26)	1.08 (0.95 to 1.23)	1.08 (0.97 to 1.19)
O ₃ (µg/m ³)	0–34.7	1 (reference)	1 (reference)	1 (reference)
	>34.7–37.3	0.83 (0.65 to 1.07)	0.88 (0.63 to 1.24)	0.68 (0.52 to 0.89)
	>37.3–39.1	0.64 (0.48 to 0.86)	0.81 (0.55 to 1.17)	0.76 (0.58 to 1.00)
	>39.1–41.8	0.62 (0.46 to 0.85)	0.82 (0.55 to 1.23)	0.73 (0.55 to 0.96)
	>41.8	0.67 (0.48 to 0.94)	0.92 (0.59 to 1.43)	0.67 (0.50 to 0.90)
	+5.6 (IQR change)	0.78 (0.66 to 0.92)	0.88 (0.71 to 1.09)	0.87 (0.76 to 1.01)
L _{night} (dB)	0–49.4	1 (reference)	1 (reference)	1 (reference)
	>49.4–49.6	0.95 (0.76 to 1.18)	1.22 (0.94 to 1.58)	1.07 (0.85 to 1.34)
	>49.6–50.3	0.96 (0.77 to 1.20)	1.23 (0.94 to 1.59)	0.97 (0.77 to 1.23)
	>50.3–53.8	0.94 (0.75 to 1.18)	1.17 (0.90 to 1.52)	0.93 (0.73 to 1.19)
	>53.8	1.05 (0.84 to 1.31)	1.09 (0.83 to 1.42)	1.14 (0.91 to 1.43)
	+2.7 (IQR change)	1.03 (0.99 to 1.07)	1.00 (0.96 to 1.05)	1.03 (0.99 to 1.07)

*HR2: Cox model with practice fitted as shared frailty. Adjusted for age, sex, ethnicity, smoking, alcohol consumption, body mass index and Index of Multiple Deprivation. For each exposure, models fit either quintiles with reference category, or IQR change.

L_{night}, night-time noise levels; NO₂, nitrogen dioxide; O₃, ozone; PM_{2.5}, particulate matter ≤2.5 µm.

tends to dominate.¹⁷ However, we were able to make use of a dispersion model with exceptionally fine resolution (20×20 m) to estimate significant changes in exposure of air pollution such as NO₂, between major roads and suburban background locations.¹⁷ Despite this, the reality was that subtle roadside changes predicted by the model were small in comparison with larger differences estimated between the areas represented by the GP practices (ICCs>0.7 for all air pollutants), suggesting most modelled air pollution variation was between (practice) areas.¹⁶ While this limited statistical power to test for any within-practice effects in the study, we did not find

evidence to suggest that the overall associations with NO₂ and PM_{2.5} were entirely explained by between-practice differences in modelled exposures.

Finally, another limitation was the incomplete information on key confounders and reliance on an area-based measure (IMD) for socioeconomic status. While mid-life obesity is a risk factor for Alzheimer's disease,⁵ the BMI measures we extracted around baseline showed that the risk declined with obesity in later life, a finding which has been observed elsewhere.³⁵ However, further adjustment for IHD, stroke, diabetes and heart failure, which would be associated with earlier unmeasured risk

factors, including individual socioeconomic status, did not explain our findings.

Context

The established body of epidemiological evidence linking long-term concentrations of air pollution to adverse health effects has mainly focused on cardiovascular disease.³⁶ The Global Burden of Disease studies, which have described the worldwide impact of air pollution, considered a wide range of outcomes (IHD, stroke, lung cancer, chronic obstructive pulmonary disease) but did not consider neurodegenerative outcomes.⁷ Research linking air pollution exposure to neurocognitive function has gradually increased from observational findings in 2002 from dogs in Mexico City,³⁷ to larger studies which assessed cognitive decline,^{38,39} and large population cohorts that specifically investigated the association in relation to diagnoses of dementia.^{10,11,40–43}

A 2015 review on the effect of long-term exposure to outdoor air pollution (15 studies) and noise (8 studies) on cognitive and psychological functions in adults showed that both exposures were separately shown to be associated with one or several measures of global cognitive function, but no study considered both exposures simultaneously, which they highlighted as a need for further research.³⁴ The same authors followed with data from the Heinz Nixdorf Recall cohort study¹³ on 4086 adults using an additively calculated global cognitive score. They concluded ‘air pollution and road traffic noise might act synergistically on cognitive function in adults’. Our study could consider both measures (air pollution and night noise), and while both showed independent associations with dementia, in a combined model any associations with noise were diminished and of borderline statistical significance.

The largest cohort studies to date investigating dementia and long-term exposure to air pollution are from North America.^{10,11,43} Chen *et al*^{10,11} used a large Canadian population-based cohort of over 2 million adults aged 55–85 years to ascertain approximately 250 000 incident dementia cases during 2001–2013. In their first analysis,¹⁰ the authors found that the risk of dementia increased with nearness to a major road (adjusted HR=1.07, 95% CI 1.06 to 1.08, for people living <50 m from a major traffic road versus >300 m). Associations were stronger among urban residents, especially those who lived in major cities. In a subsequent analysis,¹¹ they used land-use regression models to estimate associations between incident dementia and air pollution, finding significant positive associations with both PM_{2.5} and NO₂, and smaller negative associations with O₃. An IQR increase in PM_{2.5} (4.8 µg/m³) was associated with an HR of 1.04 (95% CI 1.03 to 1.05), while for NO₂ (14.2 parts per billion) HR was estimated to be 1.10 (95% CI 1.08 to 1.12). By comparison, our estimated distribution of the same pollutants within Greater London was much less spread, with IQRs approximately one-quarter in size. Therefore, comparative HRs for similar unit changes in our study are much greater

(eg, for a 1 µg/m³ change in PM_{2.5} the HR would be 1.07 compared with 1.01 from the Canadian study, for NO₂ this would be 1.02 vs 1.00). Our estimate for PM_{2.5} was more in line what was found in a large US study of Medicare enrollees for first-ever hospitalisation for dementia during 1999–2010 (HR=1.08, 95% CI 1.05 to 1.11, for a 1 µg/m³ change in PM_{2.5}). Chen *et al*¹¹ speculate that the stronger associations observed with NO₂ may be in part due to it better capturing fine-scale variability in traffic-related air pollution, whereas PM_{2.5} and O₃ have larger regional components. However the resolution of their air pollution models was coarser (1×1 km resolution) than in our study (20×20 m) and may not capture primary emissions from road traffic. While our models were able to estimate traffic-specific components of PM_{2.5},¹⁷ effect estimates remained higher for NO₂.

Some smaller studies have separated Alzheimer’s disease from dementia. In Europe, a 15-year longitudinal study in northern Swedish city found evidence of positive associations with both vascular dementia and Alzheimer’s disease and nitrogen oxide using a land-use regression model with a spatial resolution of 50×50 m.⁴¹ Comparison between participants in the highest quartile of residential exposure at baseline, versus those in the lowest, produced similar estimates for Alzheimer’s disease (HR=1.38) and vascular dementia (HR=1.47). There have been recent cohort studies from Taiwan: Jung *et al*⁴⁰ showed long-term exposure to O₃ and PM_{2.5} was shown to increase the risk of Alzheimer’s disease, while Chang *et al*⁴² found associations between dementia and NO₂ and carbon monoxide. A smaller case–control study by Wu *et al*⁴⁴ linked PM₁₀ and O₃ to an increased risk of Alzheimer’s disease and (vascular) dementia. In our study, lower O₃ was negatively associated with risk of dementia, primarily as a result of the strong negative correlation with the other modelled air pollutants.⁴⁵

Implications

The implications of linking exposure to air pollution such as NO₂ to the development of dementia, specifically Alzheimer’s disease, raise many questions.¹² The cause of these neurodegenerative diseases is still largely unknown and may be multifactorial.⁸ While toxicants from air pollution have several plausible pathways to reach the brain, how and when they may influence neurodegeneration remains speculative.^{8,30,46} Traffic-related air pollution has been linked to poorer cognitive development in young children,⁴⁷ and continued significant exposure may produce neuroinflammation and altered brain innate immune responses in early adulthood.⁴⁸ In later life, the risk for accelerated cognitive decline may involve gene–environment interactions, such as that with apolipoprotein E,⁴⁹ where evidence comes from findings in neurotoxicological experiments with mice.⁵⁰

Our observation of an association of air pollution with new dementia diagnoses among older adults living in Greater London is in contrast to an earlier analysis on these data which failed to show consistent associations

between air pollution and cardiorespiratory outcomes.¹⁶ These suggest there may be a geographical pattern specific to dementia, and potentially Alzheimer's disease, which requires further exploration nationally. In the Ontario cohort, Chen *et al* estimated that 6.1% of their total dementia cases were attributable to elevated air pollution exposure.¹¹ In our study, a theoretical shift of all patients to the bottom 20% of NO₂ exposure produces an attributable fraction of 7% (data not shown). While this would be smaller than previous population attributable fraction (PAF) estimates for dementia in the UK for a range of independent risk factors such as for hypertension or obesity,⁵ even a small PAF for dementia would be impactful, where environmental risk factors such as air pollution can be more easily modified at the population level.³⁰ There would be significant public health gains even if the impact was only to delay the progression of dementia.⁴

With the future global burden of dementia likely to be substantial,³ further epidemiological work is urgently needed to confirm and understand better recent findings linking air pollution to dementia.^{8,30} Our results suggest both regional and urban background pollutants may be as important as near-traffic pollutants. Future large-scale studies will need to rely on improved recording and linkage of dementia diagnoses across electronic systems, particularly Alzheimer's disease, where multiple sources can improve diagnostic accuracy.²⁵ Since exposure is life-long, and most cases are diagnosed in later life, historical data are also ideally required to better estimate cumulative exposure over preceding decades. In conclusion, our findings add to a growing evidence base linking air pollution and neurodegeneration and should encourage further research in this area.

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Data sharing statement Due to data restrictions, we are unable to share any aspect of the data.

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