Air pollution, pollens, and daily admissions for asthma in London 1987–92

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Abstract

***Background*—A study was undertaken to investigate the relationship between daily hospital admissions for asthma and air pollution in London in 1987–92 and the possible confounding and modifying effects of airborne pollen.**

***Methods*—For all ages together and the age groups 0–14, 15–64 and 65+ years, Poisson regression was used to estimate the relative risk of daily asthma admissions associated with changes in ozone, sulphur dioxide, nitrogen dioxide and particles (black smoke), controlling for time trends, seasonal factors, calendar effects, influenza epidemics, temperature, humidity, and autocorrelation. Independent effects of individual pollutants and interactions with aeroallergens were explored using two pollutant models and models including pollen counts (grass, oak and birch).**

***Results*—In all-year analyses ozone was significantly associated with admissions in the 15–64 age group (10 ppb eight hour ozone, 3.93% increase), nitrogen dioxide in the 0–14 and 65+ age groups (10 ppb 24 hour nitrogen dioxide, 1.25% and 2.96%, respectively), sulphur dioxide in the 0–14 age group (10 μg/m^3 24 hour sulphur dioxide, 1.64%), and black smoke in the 65+ age group (10 μg/m^3 black smoke, 5.60%). Significant seasonal differences were observed for ozone in the 0–14 and 15–64 age groups, and in the 0–14 age group there were negative associations with ozone in the cool season. In general, cumulative lags of up to three days tended to show stronger and more significant effects than single day lags. In two-pollutant models these associations were most robust for ozone and least for nitrogen dioxide. There was no evidence that the associations with air pollutants were due to confounding by any of the pollens, and little evidence of an interaction between pollens and pollution except for synergism of sulphur dioxide and grass pollen in children ($p<0.01$).**

***Conclusions*—Ozone, sulphur dioxide, nitrogen dioxide, and particles were all found to have significant associations with daily hospital admissions for asthma, but there was a lack of consistency across the age groups in the specific pollutant. These associations were not explained by confounding by airborne pollens nor was there convincing evidence that the effects of air pollutants and airborne pollens interact in causing hospital admissions for asthma.**

(*Thorax* 1998;**53**:842–848)

Keywords: air pollution; pollen; asthma

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Received 9 January 1998
Returned to authors 5 March 1998
Revised version received 22 April 1998
Accepted for publication 15 May 1998

It is widely believed that current levels of outdoor air pollution may provoke or exacerbate asthma. This is not surprising because a characteristic aspect of asthma is a tendency towards hyperreactivity to inhaled environmental gases, particles, and allergens. Experimental studies in animals and humans have shown that commonly measured pollutants including ozone (O_3), sulphur dioxide (SO_2), respirable particles, and nitrogen dioxide (NO_2) all have the potential to aggravate asthma by either direct irritation or by enhancing the effects of allergens to which the individual is sensitive.[1–4] An effect of air pollution on symptoms or use of medications has been reported mainly from areas with high levels of oxidant pollution[5–7] and some studies have only observed small changes in lung function, similar to those experienced by non-asthmatic subjects.[2] It is plausible that such effects, if occurring in an asthmatic with already compromised lung function, could lead to an increase in use of primary care or hospital services. Exposure to aeroallergens (pollens, fungal spores) is related to weather conditions and is a potential confounder in analyses of the effects of air pollution on daily hospital admissions for asthma. Experimental evidence suggests that the effects of aeroallergens may be increased by exposure to air pollution[8–10] but the importance of this biological interaction at the population level is unknown.

Analyses of daily time series of emergency hospital attendance or admissions for asthma offer a convenient method of testing the hypothesis that air pollution provokes asthma in the population at large. Taken overall, existing studies lack consistency as to the presence of effects or, where effects have been observed, the type of pollutant.[2] Few studies have addressed the issue of confounding or effect modification by pollens or examined associations in children, a subject of particular popular concern.

In this paper we attempt to address all of these questions in the context of London from 1987 to 1992. We use Poisson regression techniques to examine the association between air pollution (O_3, NO_2, SO_2, and black smoke) and daily emergency admissions for asthma in children, adults (15–64) and the elderly (65+). We examine the possible confounding effect of airborne pollens and test the hypothesis raised by chamber studies[8–10] that there is an interaction

Table 1 Summary data for daily asthma admissions, meteorological, and air pollution variables

Variable	*Days of observations*	*Mean*	*SD*	*Percentile*								
				Min	*5th*	*10th*	*25th*	*50th*	*75th*	*90th*	*95th*	*Max*
Asthma admissions/day												
All ages	1796	35.1	15.3	3	15	18	24	33	43	54	64	109
0–14 years	1796	19.5	11.1	1	6	8	12	17	25	34	40	85
15–64 years	1796	13.1	6.3	1	5	6	9	12	17	21	25	46
65+ years	1796	2.6	1.8	1	1	1	1	2	3	5	6	12
Mean temperature (°C)	1796	12.3	5.2	−5	4	6	8	12	16	20	21	29
Relative humidity (%)	1796	72.1	10.2	40	54	58	65	72	80	86	89	96
O_3, maximum 8 h average (ppb)	1613	15.5	10.9	1	2	4	8	14	21	28	36	74
O_3, maximum 1 h (ppb)	1677	20.6	13.2	0	3	5	11	20	27	36	45	94
NO_2, 24 h average (ppb)	1782	37.2	12.3	14	22	25	30	36	42	50	58	182
NO_2, maximum 1 h average (ppb)	1782	57.2	23.0	21	35	38	44	52	64	81	98	370
Black smoke, 24 h average (μg/m^3)	1793	14.6	7.0	3	7	8	10	13	18	22	26	95
SO_2, 24 h average (μg/m^3)	1793	32.0	11.7	9	16	18	24	31	38	46	52	100
Birch pollen (grains/m^3)[1]	252/915	18	42	1	1	1	1	3	18	40	94	406
Grass pollen (grains/^{3})[1]	600/915	21	37	1	1	1	2	6	18	68	104	293
Oak pollen (grains/m^3)[1]	207/915	14	28	1	1	1	1	3	13	41	73	213

[1] For warm season only. Number of days when counts were above zero.

between pollens and pollution effects. This work was part of a multi city European project (Air Pollution and Health: a European Approach (APHEA)) which used a standardised approach to the data assembly and statistical analysis.[11–13] A meta-analysis of selected asthma admissions results from APHEA has been published[14] and elsewhere[15] we have reported the results for all respiratory admissions, but not specifically for asthma. The published results for all respiratory diagnoses[15] do not address possible confounding or effect modification by aeroallergens.

Methods

The sources of health and air pollution data and the way in which the database was constructed for analysis have been described in detail elsewhere.[15] This followed the procedures adopted by APHEA[11] All air pollution variables were obtained from routine monitors sited to measure urban background concentrations. Ozone concentrations were measured by the ultraviolet absorption technique at a single background monitor in inner London and expressed as eight hour (09.00–17.00 hours) and maximum one hour averages. Nitrogen dioxide concentrations were measured by the chemiluminescence method at two urban background sites in inner London and expressed as one hour maximum and daily averages. Daily average concentrations of particles were measured using the black smoke (BS) method at four monitors in central, north, northeast, and south London; this method measures only black particles of less than 4.5 μm diameter.[16] Daily average concentrations of SO_2 were obtained from the same four sites using the acidimetric bubbler system. If up to two stations did not provide data we used a regression method to obtain an estimate of the average values across the four stations on each day.[17] Mean 24 hour temperature and humidity were calculated from data obtained from Holborn in central London.

The airborne pollen concentrations were monitored on the flat unobstructed roof of a seven storey building in North London using a Burkard volumetric spore trap. This draws air through a critical orifice at 10 l/min onto a tape on a rotating drum (speed 2 mm/h) coated with a smooth adhesive mixture of Vaseline and paraffin wax to provide a time related sample of airborne material. The tape is stained with basic fuschin and examined under ×400 magnification. Pollen grains and spores are identified with as much taxonomic detail as possible and a 24 hour average for each taxon is compiled from 12 two hour samples. This technique of pollen and spore monitoring is the standard adopted by the British Aerobiology Federation for use by the National Pollen Network. Daily counts for birch, grass, and oak are used in this analysis.

For the period April 1987 to February 1992 inclusive, counts of daily emergency admissions for asthma (ICD9 493 coded at discharge) to all National Health Service hospitals in London were obtained from the Hospital Episode System. This covers the great majority of emergency admissions for acute medical conditions such as asthma. It does not include attendance at hospital emergency departments which do not result in admission.

The statistical analysis followed the approach developed by APHEA which has been described elsewhere.[12] Details of the analysis of the London admissions data for this period were described in our previous paper on all respiratory admissions[15]) but are briefly summarised here. The general approach was to use Poisson regression to model the daily counts of asthma admissions, taking account of overdispersion and autocorrelation. We first controlled for time trends, seasonal cycles, days of the week, public holidays, and influenza epidemics. The residuals from this process were then examined in relation to temperature and humidity to identify the lag (if any) with the strongest effect and the transformation (if any) which gave the best fit. The last stage in the development of the basic model was to correct for the remaining autocorrelation of the residuals. The final model was checked and revised as necessary using autocorrelation functions, Durbin-Watson statistics, plots of fitted values and residuals, and periodograms. A log linear model with autoregressive Poisson errors was then fitted to the data. No transformation of the pollutant variable was used.

Our a priori hypothesis concerned associations with pollution on the same or previous

Table 2 Associations between air pollution and daily asthma admissions in London 1987–92. Percentage increase/decrease (95% confidence intervals). The most significant single day (l_s) and cumulative day (l_{0s}) lags are shown

Age group (years)	Season	8 h ozone Single lag	8 h ozone Cumulative lag	24 h NO_2 Single lag	24 h NO_2 Cumulative lag	24 h SO_2 Single lag	24 h SO_2 Cumulative lag	24 h BS Single lag	24 h BS Cumulative lag
0–14	Whole year	0.17 l_0 −1.56,1.94	0.49 l_{02} −1.7,2.73	1.25* l_2 0.3,2.2	1.77** l_{03} 0.39,3.18	1.64* l_1 0.29,3.01	2.04* l_{03} 0.29,3.83	0.58 l_2 −1.27,2.46	0.88 l_{03} −1.85,3.7
	Warm season	1.48 l_0 −0.51,3.50	2.69* l_{02} 0.21,5.22	1.42 l_2 −0.3,3.17	3.01* l_{03} 3.8,5.72	3.33** l_1 1.09,5.63	3.40* l_{02} 0.41,6.48	−1.33 l_2 −5.35,2.87	−4.13 l_{03} −10.18,2.32
	Cool season	−2.95* l_0 −5.80,−0.02	−5.75** l_{02} −9.4,−1.95	1.18* l_2 0.02,2.35	1.22 l_{03} −0.48,2.96	0.56 l_1 −1.16,2.32	1.24 l_{02} −0.95,3.49	1.08 l_2 −0.98,3.19	2.09 l_{03} −0.99,5.25
15–64	Whole year	3.93*** l_1 1.77,6.15	3.37** l_{02} 0.7,6.12	0.95 l_0 −0.26,2.17	0.99 l_{01} −0.36,3.36	−0.69 l_2 −2.28,0.94	−0.71 l_{02} −2.69,1.30	0.61 l_0 −1.73,3.01	0.47 l_{01} −2.17,3.18
	Warm season	4.25*** l_1 1.83,6.74	3.18** l_{02} 0.21,6.25	0.46 l_0 −1.70,2.67	0.05 l_{01} −2.45,2.61	−1.39 l_2 −3.97,1.27	−2.2 l_{02} −5.46,11.8	1.59 l_0 −3.81,7.30	−0.78 l_{01} −7.01,5.86
	Cool season	2.98 l_1 −0.61,6.70	3.74 l_{02} −0.88,8.57	1.21 l_0 −0.22,2.5	1.43 l_{01} −0.18,3.06	−0.24 l_2 −2.28,1.84	0.20 l_{02} −2.28,2.74	0.41 l_0 −2.16,3.04	0.72 l_{01} −1.28,3.71
65+	Whole year	2.67 l_2 −1.66,7.20	−2.64 l_{01} −6.93,1.86	2.96** l_2 0.67,5.31	3.14 l_{03} −0.04,6.42	2.82 l_2 −0.82,5.96	3.06 l_{03} −0.72,6.98	5.60* l_2 1.09,10.31	8.61** l_{03} 2.39,15.2
	Warm season	3.68 l_2 −1.12,8.71)	0.31 l_{01} −4.63,5.31	1.89 l_2 −2.41,6.38	−1.76 l_{03} −7.27,4.07	−2.62 l_2 −7.31,2.31	−4.27 l_{03} −9.89,1.71	7.46 l_2 −3.42,19.57	2.99 l_{03} −11.11,19.08
	Cool season	0.14 l_2 −6.87,7.68	−9.0 l_{01} −16.0,1.42	3.52* l_2 0.81,6.30	5.57** l_{03} 1.85,9.43	5.85** l_2 1.81,10.05	7.28** l_{03} 2.19,12.62	4.20 l_2 −0.81,9.46	7.91* l_{03} 0.98,15.32
All ages	Whole year	6.90 l_1 −0.07,1.02	0.42 l_{02} −1.31,2.17	1.25*** l_2 0.49,2.02	2.05** l_{03} 0.96,3.15	1.64* l_1 0.54,2.75	2.75*** l_{03} 1.22,4.30	1.22 l_2 −0.31,2.78	2.35* l_{03} 0.16,4.58
	Warm season	2.21** l_1 0.62,3.82	2.10* l_{02} 0.13,4.10	1.15 l_2 −0.25,2.57	1.54 l_{03} −0.54,3.67	2.02* l_1 0.22,3.85	2.60* l_{03} 0.02,5.25	−0.61 l_2 −3.94,2.84	−1.10 l_{03} −6.26,4.34
	Cool season	−3.17** l_1 −5.44,−0.84	−4.31* l_{02} −7.27,−1.26	1.30** l_2 0.38,2.23	2.26*** l_{03} 0.94,3.59	1.41 l_1 0.0,2.83	2.83** l_{03} 0.89,4.81	1.66 l_2 −0.04,3.37	3.07* l_{03} 0.65,5.56

BS = black smoke.
*p<0.05, **p<0.01, ***p<0.001.

two days. The most significant single lag was selected whether the effect was positive or negative. We also examined the effect of cumulative lags up to three days. The effects of each air pollutant were examined for the whole year and for the "warm" (April to September) and "cool" (October to March) seasons separately. We analysed the effects of pollens in the warm season by either including all warm season days or only those days for which the pollen count was greater than zero. In examining the interaction between pollens and air pollutants we postulated a concurrent rather than sequential effect so that, in these models, the best respective lag for both pollen and pollutant was used. Where a pollutant was found to have a significant effect the effect of putting a second pollutant into the model was examined.

The results are presented as a percentage increase associated with a 10 unit increase in pollutant level. This was calculated by the formula $100 \times (1—\exp(\beta \text{ coefficient} \times 10)—1)$. A 1% relative increase corresponds to a relative risk of 1.01. A significance level of 5% (two sided) is used.

Results

The descriptive statistics of the admissions and environmental data are shown in table 1. The associations between the various air pollutants and asthma admissions are shown in table 2 by age and season. For the all-ages group over the whole year, significant associations were observed with NO_2, SO_2 and black smoke, with the cumulative lags tending to show stronger and more significant effects. Some of these associations have p values of <0.001 and provide good evidence for a relationship even after the Bonferroni correction for 24 tests (eight pollutants and three seasons).

Ozone was negatively associated with admissions in the 0–14 age group (whole year and cool season) and positively with admissions in the 15–64 age group (whole year and warm season). The seasonal differences in the effects of ozone in these two age groups were statisti-

Table 3 Two pollutant models for those pollutants with significant associations in the single pollutant models. Effect of row pollutant when the column pollutant is entered into the model. Percentage change in admissions for 10 unit change in pollutant level (95% confidence limits)

Age (years)	Season	Pollutant (lag)	Single pollutant model	8 h O_3	24 h NO_2	24 h SO_2	24 h BS
0–14	All year	NO_2 (2)	1.25 (0.3,2.2)*	1.13 (−0.10,2.36)	—	0.97 (−0.05,1.99)	2.26 (0.83,3.71)***
		SO_2 (1)	1.64 (0.29,3.01)*	1.77 (0.22,3.36)*	1.23 (−0.22,2.69)	—	1.66 (0.23,3.12)*
	Warm	SO_2 (1)	3.33 (1.09,5.63)**	3.35 (0.89,5.87)**	2.92 (0.58,5.32)*	—	3.66 (1.35,6.02)**
	Cool	O_3 (0)	−2.95 (−5.80,−0.02)*	—	−2.91 (−5.77,0.03)	−2.92 (−5.80,0.04)	−2.95 (−5.81,−0.01)*
		NO_2 (2)	1.18 (0.02,2.35)*	0.91 (−0.66,2.51)	—	1.06 (−0.17,2.29)	1.84 (−0.03,3.75)
15–64	All year	O_3 (1)	3.93 (1.77,6.15)***	—	4.00 (1.83,6.22)***	4.04 (1.86,6.27)***	3.96 (1.78,6.18)***
	Warm	O_3 (1)	4.25 (1.83,6.74)***	—	4.31 (1.87,6.82)***	4.82 (2.28,7.42)***	4.15 (1.73,6.63)***
65+	All year	NO_2 (2)	2.96 (0.67,5.31)**	4.51 (1.43,7.69)**	—	2.49 (−0.25,5.31)	1.88 (−1.49,5.36)
		BS (2)	5.60 (1.09,10.31)*	7.56 (1.19,14.34)*	2.92 (−3.56,9.85)	4.56 (−0.88,10.29)	—
	Cool	NO_2 (2)	3.52 (0.81,6.30)*	5.14 (0.69,9.79)*	—	2.10 (−1.08,5.39)	4.47 (−0.04,9.19)
		SO_2 (2)	5.85 (1.81,10.05)**	7.84 (2.48,13.48)**	4.19 (−0.53,9.13)	—	5.29 (0.42,10.40)*
All ages	All year	NO_2 (2)	1.25 (0.49,2.02)***	1.08 (0.12,2.05)*	—	0.99 (0.18,1.81)*	1.23 (0.47,2.00)**
		SO_2 (1)	1.64 (0.54,2.75)*	1.48 (0.24,2.73)*	1.14 (−0.04,2.33)	—	1.54 (0.36,2.73)*
	Warm	O_3 (1)	2.21 (0.62,3.82)**	—	1.97 (0.35,3.62)*	1.99 (0.40,3.61)*	2.18 (0.59,3.79)**
		SO_2 (1)	2.02 (0.22,3.85)*	1.91 (0.05,3.81)*	1.64 (−0.23,3.56)	—	2.18 (0.32,4.07)*
	Cool	O_3 (1)	−3.17 (−5.44,0.84)**	—	−2.90 (−5.26,−0.49)*	−3.01 (−5.36,−0.60)*	−2.92 (−5.24,−0.54)*
		NO_2 (2)	1.30 (0.38,2.23)**	0.50 (−0.79,1.81)	—	1.10 (0.12,2.08)*	1.29 (0.37,2.22)**
		SO_2 (1)	1.41 (1.00,2.83)*	−0.09 (−1.61,1.82)	0.83 (−0.67,2.34)	—	1.11 (−0.41,2.66)

BS = black smoke.
*p<0.05; **p<0.01; ***p<0.001.

Table 4 Percentage increase in daily asthma admissions associated with 10 unit increase in pollen grain counts during the warm season in London, 1987–91. 95% confidence limits are shown in parenthesis together with the corresponding lag period (l_n). Where a statistically significant association was observed for other lags, these are shown in parentheses

Age group	*Birch pollen*		*Grass pollen*		*Oak pollen*	
0–14 years	0.90* (0.14,1.67)	l_2	−1.13* (−1.96,0.0)	l_0	−1.62* (−3.21,0.0)	$l_{0(1)}$
15–64 years	1.11* (0.11,2.12)	l_1	−0.073 (−1.71,0.26)	l_1	1.89* (0.0,3.80)	l_1
65+ years	−0.77 (−3.37,1.9)	l_0	−0.63 (−2.69,1.48)	l_0	−2.6 (−6.37,1.31)	l_1
All ages	0.78* (0.15,1.42)	$l_{2(1)}$	−1.16*** (−1.82,−0.5)	l_0	−1.44* (−2.71,−1.04)	$l_{0(1)}$

cally significant. NO_2 was significantly associated with admissions in the 0–14 age group (whole year and warm season) and in the 65+ age group (cool season). SO_2 was associated with admissions in the 0–14 age group (whole year and warm season) and in the 65+ age group (cool season), while black smoke was associated with admissions in the 65+ age group (whole year and cool season).

The various pollutants covary to some extent and this covariation is not constant across the seasons. For example, the correlation between ozone and NO_2 is positive in the warm season and negative in the cool season. For every significant association, two-pollutant models were examined to obtain insight into which single pollutant might influence asthma admissions independently of the effects of others. The results of this analysis are shown in table 3. The results did not follow a pattern that is easy to summarise. We draw attention to those analyses in which the effect of a particular pollutant remained significant after each of the other three pollutants was included in the model.

In the all-year analysis the effects of O_3 (15–64 age group) and NO_2 (all-ages) were robust to inclusion of each of the other three pollutants. In the warm season analysis similarly robust findings were obtained for SO_2 (0–14 age group) and ozone (15–64 age group and all-ages). In the cool season the only robust result was for the negative effect of ozone in the all-ages analysis.

The effect of birch, grass, and oak pollens on admissions is shown in table 4. No consistent pattern is apparent. There is a significant positive effect of birch pollen in the 0–14 and 15–64 age groups, a significant negative effect of grass pollen in the 0–14 age group, and a significant negative effect of oak pollen in the 0–14 and 15–64 age groups. Because the production and dispersal of pollens is related to weather conditions, it is possible that any effects of pollens on asthma admissions could confound the effects of pollutants in the relevant period of the year. There was little correlation between birch pollen and any pollutant but grass pollen was correlated positively with ozone (r = 0.122) and SO_2 (r = 0.115) and negatively with black smoke (r = –0.117). Oak pollen was positively related to ozone (r = 0.138) and NO_2 (r = 0.182).

To examine the possibility of confounding by pollens the effects of those pollutants found to have warm season effects were examined after inclusion of each of the pollen categories in the model. As table 5 clearly shows, the pollutant effects are not influenced by introducing pollen into the model. The analysis was repeated for only those days on which the pollen count was above zero with the same result. Table 6 tests the hypothesis that there is a pollution/pollen interaction by comparing the effects of pollutants on days when pollens were present with those when they were not. The only interaction in a positive direction—that is, as hypothesised—was between SO_2 and grass pollen in the 0–14 age group ($p < 0.01$). In two comparisons (ozone and birch pollen and ozone and oak pollen in the all-age group) the

Table 5 Results of two pollutant models examining the effect of pollen on estimates of individual pollutant effects. Analysis is confined to the warm season, and to pollutants which were significant in the unipollutant models (see table 2)

Age (years)	*Pollutant (lag)*	*Single pollutant effect*	*Birch*	*Grass*	*Oak*
0–14	24 h SO_2 (1)	3.33**	3.17 (0.92,5.47)**	3.30 (1.05,5.59)**	3.34 (1.0,5.63)**
15–64	8 h O_3 (1)	4.25***	4.30 (1.88,6.78)***	4.28 (1.86,6.76)***	4.16 (1.74,6.64)***
	24 h SO_2 (2)	−1.39	−1.62 (−4.21,1.04)	−1.36 (−3.96,1.30)	−1.34 (−3.93,1.32)
All ages	8 h O_3 (1)	2.21**	2.23 (0.64,3.83)**	2.24 (0.66,3.85)**	2.22 (0.64,3.83)**
	24 h SO_2 (1)	2.02*	1.82 (0.02,3.65)*	2.10 (0.30,3.93)*	2.01 (0.22,3.84)*

Table 6 Results of two pollutant models examining the effect of pollen on estimates of individual pollutant effects. Analysis is confined to the warm season and to pollutants which were significant in the unipollutant models

Age (years)	*Pollutant (lag)*	*Days*	*Birch*	*Grass*	*Oak*
0–14	8 h O_3 (0)	Pollen >0	−0.47 (−4.39,3.61)	0.94 (−1.31,3.23)	−1.26 (−5.30,2.95)
		No pollen	1.83 (−0.33,4.03)	2.66 (−0.43,5.85)	2.07 (−0.09,4.27)
					3.34 (1.0,5.63)**
	24 h SO_2 (1)	Pollen >0	3.51 (−1.20,8.45)	5.78 (3.04,8.59)*** [1]	3.99 (−0.58,8.76)
		No pollen	3.27 (0.87,5.73)**	0.14 (−2.97,3.34)	3.21 (0.84,5.63)**
15–64	8 h O_3 (1)	Pollen >0	2.79 (−1.95,7.76)	4.64 (1.98,7.37)***	1.42 (−3.43,6.51)
		No pollen	4.62 (2.00,7.30)***	3.12 (−1.01,7.43)	4.83 (2.24,7.50)***
	24 h SO_2 (2)	Pollen >0	0.99 (−4.38,6.66)	−1.12 (−4.15,2.01)	−2.54 (−7.74,2.96)
		No pollen	−1.56 (−4.36,1.33)	−1.89 (−5.62,1.99)	−1.15 (−3.89,1.67)
All ages	8 h O_3 (1)	Pollen >0	−2.81 (−5.84,0.31) [2]	2.20 (0.45,3.98)**	−2.69 (−5.82,0.54) [3]
		No pollen	3.38 (1.67,5.12)***	2.34 (−0.21,4.95)	3.27 (1.57,5.00)***
	24 h SO_2 (1)	Pollen >0	2.44 (−1.40,6.44)	3.19 (1.05,5.38)**	1.09 (−2.55,4.87)
		No pollen	2.00 (0.08,3.96)**	0.27 (−2.28,2.89)	2.20 (0.29,4.14)*

[1]Interaction $p<0.01$; [2]interaction $p<0.001$; [3]interaction $p<0.001$.

Table 7 Summary of time series studies of air pollution and daily admissions or emergency room attendance for asthma. The rows are sorted by whether the analysis was for "all year" (including across seasons) and by "summer" (warm half of the year) or "winter" (cool half of the year). Under the various age groups where a pollutant is within a parenthesis, the association was negative

Author	Reference no.	Year	Place	Ads/ ER	Season	Months	O_3	NO_2	SO_2	Particles	0–14 yrs	15–64 yrs	65+ yrs	All ages
Anderson	This paper		London	Ads	AY		+	+	+	BS	NO_2,SO_2	O_3	NO_2,BS	NO_2,SO_2,BS
Buchdahl	20	1996	London	ER	AY		+	+	+	—	O_3,SO_2	—	—	—
Dab	21	1996	Paris	Ads	AY		+	+	+	PM_{13},BS	SO_2	O_3,NO_2	—	SO_2,NO_2
Ponka	22	1996	Helsinki	Ads	AY		+	+	+	TSP	NS	NS	SO_2	—
Romieu	23	1995	Mexico City	ER	AY	Jan–Jun	+	—	+	—	O_3,SO_2	—	—	—
Schwartz	24	1993	Seattle	ER	AY		+	—	+	PM_{10}	PM_{10}	PM_{10}	NS	—
Sunyer	14	1996	Barcelona	ER	AY		+	+	+	BS	—	O_3	—	—
Anderson	This paper		London	Ads	S	Apr–Sept	+	+	+	BS	O_3,NO_2,SO_2	O_3	NS	O_3,SO_2
Bates	25	1990	Vancouver	ER	S		+	+	+	SO_4,COH	SO_4	SO_2,SO_4	SO_4	—
Bates	26	1987	Ontario	Ads	S	July–Aug	+	+	+	SO_4,COH	NS	—	—	SO_2,O_3,SO_4
Burnett	27	1994	Ontario	Ads	S	May–Aug	+	—	—	SO_4	O_3 SO_4	O_3 SO_4	NS	O_3,SO_4
Castellsague	28	1995	Barcelona	ER	S		+	+	+	BS	—	BS, NO_2	BS,NO_2	—
Cody	29	1992	N Jersey	ER	S	May–Aug	+	—	+	—	—	—	—	O_3
Delfino	30	1994	Montreal	Ads	S	Jun–Sept	+	—	—	PM_{10},$PM_{2.5}$ H^+,SO_4	—	—	_	PM_{10},SO_4
Schouten	31	1996	Amsterdam	Ads	S	Apr–Sept	+	+	+	BS	—	—	—	SO_2
Steib	32	1996	St John, NB	ER	S	May–Sept	+	+	+	SO_4,TSP	NS	O_3	O_3	O_3
Thurston	33	1994	Toronto	Ads	S		+	—	—	SO_4,H^+	—	—	—	O_3,SO_4,H^+
Thurston	34	1992	New York	Ads	S		+	—	—	SO_4,H^+	—	—	—	O_3,SO_4,H^+
Walters	35	1994	B'ham, UK	Ads	S	June–Aug	—	—	+	BS	—	—	—	NS
Anderson	This paper		London	Ads	W	Oct–Mar	+	+	+	BS	(O_3),NO_2	NS	NO_2,SO_2,BS	(O_3),NO_2,SO_2,BS
Bates	25	1990	Vancouver	ER	W		+	+	+	SO_4,COH	NS	NS	SO_2,SO_4	—
Bates	26	1987	Ontario	Ads	W	Jan–Feb	+	+	+	SO_4,COH	(O_3)	—	—	NS
Castellsague	28	1995	Barcelona	ER	W		+	+	+	BS	—	NO_2	—	—
Schouten	31	1996	Amsterdam	Ads	W	Oct–Mar	+	+	+	BS	—	—	—	NS
Walters	35	1994	B'ham, UK	Ads	W	Dec–Feb	—	—	+	BS	—	—	—	BS,SO_2

Ads = admissions; ER = emergency room admissions or attendance at accident and emergency departments; TSP = total suspended particles; PM = suspended particles; SO_4 = sulphate; COH = coefficient of haze; H^+ = hydrogen ion concentration (a measure of acid aerosols); AY = all year; S = summer/warm season; W = winter/cool season; BS = black smoke; NS = no pollutant significant, — = no information on that age group.

interaction was significantly negative ($p < 0.001$ in each case).

Discussion

This is one of the most comprehensive investigations of daily asthma admissions and air pollution yet reported, and one of the few to take airborne pollen into account and to examine interactions between pollution and pollen levels. We found associations between all of the four air pollutants and daily asthma admissions, but a lack of consistency across age groups and seasons. Some of the associations were not strongly significant and others were weakened or became non-significant after including another pollutant in the model. For all ages combined the most robust associations were with SO_2 and NO_2. When analysed by age the most robust associations were for SO_2 in the warm season in children, and for ozone in younger adults, also in the warm season. With the exception of ozone, there was a tendency for the cumulative lags to have a stronger effect.

Although the statistical method employed was a widely accepted one,[13] its appropriateness and the manner in which potential confounders, especially weather and cyclical factors, are controlled have both been criticised.[18] Studies which have addressed these issues in the context of daily mortality have been reassuring[19] but may be less relevant to admission data which may require more complex models than mortality data. This applies especially to children because of their greater susceptibility to respiratory epidemics and the effects of school holidays. In addition, it must also be recognised that large numbers of statistical tests were performed using a variety of lags, and it is therefore also possible that some of the significant results were due to chance. For this reason more weight should be placed on the larger and more strongly significant findings, especially those which are consistent across seasons and age groups and robust to the inclusion of other pollutants in the model.

Our assessment of exposure was based on a relatively small number of monitors and may not have been a good indicator of personal exposure to outdoor pollution. Where several monitors were available, there was a significant and often strong correlation between them. Since this study the number of automatic monitors in London has expanded greatly. These new monitors, which cover both central and suburban London, tend to show good tracking between background levels of ozone, NO_2 and PM_{10} particles, though less so for SO_2.

Twenty one other studies of air pollution and daily asthma admissions were identified in the literature. Of these, 15 appeared to have a satisfactory methodology and these, together with the present study, are listed in table 7 to obtain an overview of age groups and pollutants studied and the direction and statistical significance of the associations reported. Calculation of summary estimates using meta-analysis was outside the scope of this paper and would, in any case, have been difficult because the studies differed in many respects, including methods, statistical power, the pollutants investigated, and the age ranges reported. Our assessment of consistency will rely mainly on whether statistically significant findings were reported. In the all-age group three of 14 studies did not find significant associations with any of the pollutants assessed and the proportions with significant findings for ozone, SO_2, NO_2 and particles were 7/14, 6/12, 2/9, and 7/15, respectively. For the adult age group (15–64) three out of 13 did not find significant associations and the proportions with significant asso-

ciations with ozone, SO_2, NO_2 and particles were 6/13, 1/12, 3/13, and 3/13, respectively. One of the ozone associations was negative. Similarly, in children, 4/13 did not find significant associations and the proportions with significant associations with ozone, SO_2, NO_2 and particles were 6/11, 5/12, 3/13, and 2/11, respectively. Two of the associations with ozone were negative (both in the winter season). Taken overall, it is apparent that the evidence is not coherent as to whether there is an effect of pollution or the responsible pollutant. Ozone, SO_2 and particles were significant in no more than half of all studies and only about a quarter found significant effects for NO_2.

Some of this inconsistency may result from false negative results arising from lack of statistical power or from false positive results due to chance, multiple significance testing, post hoc hypothesis testing, or publication bias. It could also result from differences between cities in the pollutant levels and prevailing mixtures. Differences between the age-specific results may also reflect differences in the clinical and pathological nature of asthma and its provoking factors at different stages of life. Many of the pollutants considered were not independent of one another and may have been indicating some other causal pollutant which was not measured. For example, summer pollution comprises a complex mixture and varying relationships of gaseous pollutants such as ozone and SO_2 and secondary particles such as sulphates, nitrates and associated acids. Significant associations between hospital admissions for asthma and individual pollutants should not therefore be interpreted narrowly as necessarily being an effect of that pollutant. Conversely, the lack of strong associations with black smoke does not exclude an effect of particles such as sulphates not measured by this technique.

Debate about the causal nature of associations between daily mortality and particle pollution has been dominated by issues of methodology, potential confounding, and biological plausibility. A major argument in favour of causality has been the consistency of results obtained from a wide variety of cities throughout the world. In the case of asthma admissions lack of consistency weakens the argument for causality. Perhaps the effects of outdoor air pollution on asthma admissions are more dependent on local environments and population vulnerability than is the case for particles and mortality. If this is the case, results from one area should not be assumed to apply to another.

Hospital admissions for asthma may also be influenced by ambient aeroallergens. Extreme examples are point source epidemics such as those associated with the unloading of soy beans[36] and with rye grass pollen in association with thunderstorms.[37] The rise in admissions in the spring has been attributed to pollens.[38] A number of studies have not found associations between pollens and daily admissions or emergency room attendances for asthma.[39–41] One explanation could be that pollens are generally too large to penetrate to the small airways. On the other hand, fungal spores which are smaller (and hence more respirable) have been associated with asthma admissions.[41 42] In the present study we are confident that the observed associations between admissions and air pollutants are most unlikely to have been confounded by pollens. It also seems unlikely that there is an interaction between pollens and air pollutants. Further work with more recent data will investigate whether the same is true for airborne fungal spores.

Chamber studies have found evidence of interactions between aeroallergens and gaseous ambient pollutants in their effects on bronchial hyperresponsiveness.[8–10 43] We found little evidence to suggest that this mechanism occurs in the ambient situation, apart from the interaction between SO_2 and grass pollen in children's asthma admissions which requires confirmation in further studies. The chamber study of Devalia *et al*[43] found evidence of an interaction between pollens and a mixture of NO_2 and SO_2 but we did not address the question of interactions with mixtures in this data set.

We conclude that there is evidence that all of the pollutants may have an effect on asthma admissions but that there is a lack of consistency across the age groups in the specific pollutant responsible. Associations with pollutants were not confounded by airborne pollens and there was little evidence for an interaction with pollens. These results, when taken together with 15 published studies of air pollution and daily asthma admissions, indicate that the evidence linking air pollution to asthma admissions lacks consistency.

This study was funded by the National Asthma Campaign (Grant 178) and the European Commission, DGXII, Environment 1991–94 Programme (EV5V CT92–0202).

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