

ORIGINAL ARTICLE

Ambient air pollution and emergency department visits for asthma: a multi-city assessment of effect modification by age

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Previous studies have found strong associations between asthma morbidity and major ambient air pollutants. Relatively little research has been conducted to assess whether age is a factor conferring susceptibility to air pollution-related asthma morbidity. We investigated the short-term relationships between asthma emergency department (ED) visits and ambient ozone (O₃), carbon monoxide (CO), nitrogen dioxide (NO₂), sulfur dioxide (SO₂), and fine particulate matter (PM_{2.5}) in Atlanta (1993–2009), Dallas (2006–2009), and St. Louis (2001–2007). City-specific daily time-series analyses were conducted to estimate associations by age group (0–4, 5–18, 19–39, 40–64, and 65+ years). Sub-analyses were performed stratified by race and sex. City-specific rate ratios (RRs) were combined by inverse-variance weighting to provide an overall association for each strata. The overall RRs differed across age groups, with associations for all pollutants consistently strongest for children aged 5–18 years. The patterns of association across age groups remained generally consistent when models were stratified by sex and race, although the strong observed associations among 5–18 year olds appeared to be partially driven by non-white and male patients. Our findings suggest that age is a susceptibility factor for asthma exacerbations in response to air pollution, with school-age children having the highest susceptibility.

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INTRODUCTION

Many epidemiologic studies have documented relationships between ambient air pollution and asthma.¹ Adverse effects of ambient air pollution on asthma appear to disproportionately affect children,^{2–9} who also have the highest prevalence of asthma.¹⁰ The increased susceptibility of children may be due to physiological differences between adults and children (underdeveloped pulmonary and immune systems and smaller airways that become more obstructed when inflamed) and higher levels of outdoor physical activity in children.^{11–15} However, many previous studies focus exclusively on either pediatric asthma or elderly populations;^{16–19} only limited previous studies consider whether and how associations differ by age group. For example, a study of severe asthma morbidity in New York City found that children aged 6–18 years old had a higher risk of hospitalization following short-term increases in PM_{2.5} and O₃ compared with adults aged 19–49.⁵ Similarly, a study of asthma-related emergency department (ED) visits and air pollution in Canada found that children aged 2–14 years were most affected by short-term increases in ambient CO, NO₂, and SO₂ compared with older adolescents and adults.⁴ Analyses such as these comparing air pollution effects across age groups can help to identify susceptible populations — an essential component for both focused prevention efforts and accurate risk assessment. However, given the focus of these previous studies on single cities, it is unclear how generalizable the results are.

Here, we investigated short-term associations between ambient air pollution concentrations and asthma ED visits across five age groups in three US cities (Atlanta, GA; Dallas, TX; and St. Louis, IL-MO). Additional stratification by sex and race was considered to examine whether the differences in asthma–air pollution associations across age groups may be explained by sex and race.

METHODS

Data

Air quality and ED visit data were collected in 3 metropolitan areas: 20 counties around Atlanta (years 1993–2009), 12 counties around Dallas (years 2006–2009), and 16 counties around St. Louis (years 2001–2007). The air quality data included daily population-weighted average concentrations of ambient 8 h maximum O₃ (p.p.b.), 1 h maximum CO (p.p.m.), 1 h maximum NO₂ (p.p.b.), 1 h maximum SO₂ (p.p.b.), and 24 h average PM_{2.5} (μg/m³). The population-weighted averages were calculated using data from all available monitors for each pollutant in the study regions. We included monitors from the US Environmental Protection Agency Air Quality System in all three cities, the SouthEastern Aerosol Research and Characterization (SEARCH) network in Atlanta, and the Assessment of the Spatial Aerosol Composition (ASACA) network in Atlanta. The monitoring data were first spatially interpolated across the study's geographic domain and then a population-weighted average concentration estimate was derived using tract-level population estimates from the 2010 US Census.²⁰ Daily temperature and dew-point temperature data were obtained from the National Climate Data Center.

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Table 1. Descriptive statistics of population weighted averages of ambient pollutant concentrations in Atlanta (1993–2009), Dallas (2006–2009), and St. Louis (2001–2007).

Pollutant	City	Daily mean	SD	IQR
O ₃ (p.p.b.)	Atlanta	43.7	19.1	27.0
8 h maximum	Dallas	42.5	15.5	21.6
	St. Louis	37.3	19.4	28.7
CO (p.p.m.)	Atlanta	0.57	0.36	0.38
1 h maximum	Dallas	0.52	0.32	0.30
	St. Louis	0.90	0.51	0.50
NO ₂ (p.p.b.)	Atlanta	21.1	8.6	11.4
1 h maximum	Dallas	23.2	10.4	16.4
	St. Louis	28.1	8.6	12.0
SO ₂ (p.p.b.)	Atlanta	10.7	9.5	11.0
1 h maximum	Dallas	2.7	2.9	1.8
	St. Louis	10.7	6.1	7.6
PM _{2.5} (μg/m ³)	Atlanta	14.1	6.8	8.6
24 h average	Dallas	11.1	4.7	5.9
	St. Louis	13.6	6.5	8.0

Patient-level ED visit data were obtained from individual hospitals and the Georgia Hospital Association for Atlanta, from the Dallas Fort Worth Hospital Council Foundation for Dallas, and from the Missouri Hospital Association for St. Louis. Asthma ED visits were identified using the primary International Classification of Diseases, 9th Revision (ICD-9) diagnosis codes of either 493 (asthma) or 786.07 (wheeze). Identified visits were aggregated by day to obtain daily counts of asthma ED visits for each city, overall and for five age groups: 0–4, 5–18, 19–39, 40–64, and 65+ years. We used these data in accordance with our data use agreements with the hospitals and hospital associations from which the data were received. The Emory University Institutional Review Board approved this study and granted exemption from informed consent requirements, give the minimal risk nature of the study and the infeasibility of obtaining informed consent from individual patients for the large number of ED visit records examined in this study.

Analysis

For each age group, daily time-series Poisson regression models were used to assess the relationship between asthma ED visit counts and ambient pollutant concentrations. Analyses were conducted separately for each city and for each age group. In these analyses, our *a priori* temporal metric for all air pollutant concentrations was a 3-day moving average (of the current day, the previous day, and 2 days prior), chosen based on our previous research.^{15,21,22} The models controlled for meteorology via natural cubic splines with 3 degrees of freedom (d.f.) of lag 0 minimum temperature, 2-day moving average (of the previous day and 2 days prior) minimum temperature, and 2-day moving average (of the previous day and 2 days prior) dew point temperature. Temporal controls included indicator variables for day of week, federal holidays, and days commonly celebrated as holidays (e.g., the day after Thanksgiving) and a natural cubic spline of time (d.f. = 8 per year). The models also included indicator variables for the periods when there were changes in the number of hospitals that contributed to the total ED counts over time in each city. Standard errors of the model coefficients were scaled to account for over-dispersion in ED counts.

Rate ratios (RRs) obtained for each city were scaled to a pollutant-specific standard unit. The standard unit for each pollutant was determined as the interquartile range (IQR) of data combined across all three cities, and were weighted slightly toward the cities with longer study periods: 28 p.p.b. for O₃, 0.5 p.p.m. for CO, 12 p.p.b. for NO₂, 5 p.p.b. for SO₂, and 8 μg/m³ for PM_{2.5}. Pairwise statistical significance for the difference in age-specific RRs was assessed based on standard errors obtained from independent stratified analyses at a type I error rate of 0.05, assuming that the RRs estimated from the separate data sets were not correlated. Inverse-variance weighted averages of the RRs across the three cities were calculated to provide a combined estimate of association for each pollutant.

Several sensitivity analyses on model specification were performed. Various degrees of freedom for all non-linear effects were explored as well

Table 2. Mean daily counts of asthma ED visits in Atlanta (1993–2009), Dallas (2006–2009), and St. Louis (2001–2007) by age group: total and by sex and race.

Age group	Category	Subcategory	Atlanta ^a	Dallas	St. Louis
0–4 years	Total		16.78	16.91	11.98
	Sex	Male	10.42	11.16	7.64
		Female	6.24	5.75	4.34
	Race	White	2.22	3.74	4.21
		Non-white	4.50	13.17	7.38
5–18 years	Total		18.24	25.75	15.63
	Sex	Male	10.75	16.02	9.05
		Female	7.30	9.73	6.58
	Race	White	2.78	5.91	4.72
		Non-white	6.20	19.85	10.32
19–39 years	Total		13.36	15.52	12.21
	Sex	Male	4.65	5.68	4.59
		Female	8.53	9.84	7.62
	Race	White	4.39	5.93	5.13
		Non-white	6.16	9.59	6.30
40–64 years	Total		11.33	13.99	8.69
	Sex	Male	3.60	4.17	2.47
		Female	7.62	9.82	6.22
	Race	White	3.68	6.21	3.89
		Non-white	4.53	7.78	4.13
65+ years	Total		1.53	2.06	1.06
	Sex	Male	0.49	0.56	0.28
		Female	1.04	1.50	0.78
	Race	White	0.75	1.22	0.57
		Non-white	0.48	0.84	0.38

^aAtlanta data were missing a large portion of race data between 1993 and 2006.

as different meteorological controls, such as the use of maximum temperature versus minimum temperature. Sub-analyses were also performed to examine whether the pattern of age-specific associations between pollutant concentrations and asthma ED visits differed by sex and race. For these analyses, race was dichotomized into white and non-white (black, Hispanic, and other). Race-specific models in Atlanta were only considered for 1993 through 2006 because information on race was unavailable after 2006. Atlanta data between 1993 and 2006 were also missing race information to varying extents by age group (as high as 56% for asthma ED visits in the 0–4 year age category). All analyses were performed in R 2.15.1 (R Foundation for Statistical Computing, Vienna, Austria).

In time-series analyses, power is a function of both time-series length and daily outcome counts, as well as factors that are specific to the pollutant under consideration such as the degree of correlation between the pollutant and other variables in the model and the magnitude of the effect estimate. Based on previous power calculations for similar models in another study,²³ we expected that power would be good for detecting associations with asthma ED visit counts in age groups < 65 years for all of our pollutants in Atlanta and St. Louis due to the time-series lengths in those cities and daily ED visit counts generally close to or more than 10 per day. Power was expected to be lower in Dallas, which had a shorter time series. Power was also anticipated to be lower in sub-analyses by gender and race.

RESULTS

Descriptive statistics for the pollutants are shown in Table 1. St. Louis had a higher mean concentration of CO (0.90 p.p.m.) than Atlanta (0.57 p.p.m.) and Dallas (0.52 p.p.m.), and a lower mean concentration of O₃ (37.3 p.p.b.) than Atlanta (43.7 p.p.b.) and Dallas (42.5 p.p.b.). Dallas had a lower mean SO₂ concentration (2.7 p.p.b.) than Atlanta (10.7 p.p.b.) or St. Louis (10.7 p.p.b.).

Asthma ED counts totaled 389 863 in Atlanta (with a mean of 62.8 visits/day), 102 155 in Dallas (with a mean of 76.3 visits/day), and 119 952 in St. Louis (with a mean of 50.6 visits/day). Mean

Table 3. Rate ratios for the association between a standard unit increase in 3-day moving average pollutant concentrations and asthma ED visits in Atlanta (1993–2009), Dallas (2006–2009), and St. Louis (2001–2007).^a

Pollutant	Age group	Atlanta		Dallas		St. Louis		Weighted average	
		RR	95% CI	RR	95% CI	RR	95% CI	RR	95% CI
O ₃	0–4	1.00	0.98, 1.03	1.00	0.94, 1.07	1.07 ^b	1.04, 1.10	1.03 ^{b,c}	1.01, 1.05
	5–18	1.05 ^b	1.01, 1.08	1.01	0.94, 1.07	1.16 ^b	1.09, 1.22	1.07 ^b	1.04, 1.10
	19–39	1.04 ^b	1.01, 1.07	1.05	0.99, 1.11	0.99 ^c	0.93, 1.04	1.03 ^c	1.00, 1.05
	40–64	1.01	0.98, 1.04	1.01	0.95, 1.07	1.02 ^c	0.96, 1.08	1.01 ^c	0.98, 1.04
	65+	1.01	0.96, 1.07	1.01	0.91, 1.13	1.03	0.92, 1.17	1.03	0.97, 1.09
CO	0–4	1.02 ^b	1.00, 1.03	0.99	0.95, 1.04	1.01	1.00, 1.02	1.01 ^{b,c}	1.00, 1.02
	5–18	1.02 ^b	1.00, 1.04	1.03	0.99, 1.08	1.04 ^b	1.02, 1.06	1.03 ^b	1.02, 1.05
	19–39	1.01	0.99, 1.03	1.00	0.96, 1.04	1.00	0.98, 1.03	1.00 ^c	0.99, 1.02
	40–64	1.03 ^b	1.01, 1.05	0.99	0.95, 1.03	0.99 ^c	0.96, 1.01	1.00 ^c	0.99, 1.02
	65+	0.98	0.95, 1.02	1.01	0.94, 1.08	0.96 ^c	0.91, 1.01	0.99 ^c	0.96, 1.02
NO ₂	0–4	1.02 ^b	1.00, 1.03	0.99	0.95, 1.02	1.03 ^b	1.01, 1.05	1.02 ^{b,c}	1.01, 1.03
	5–18	1.04 ^b	1.02, 1.06	1.03 ^b	1.00, 1.07	1.08 ^b	1.05, 1.12	1.05 ^b	1.04, 1.07
	19–39	1.01	0.99, 1.03	1.04 ^b	1.00, 1.07	1.00 ^c	0.97, 1.03	1.02 ^{b,c}	1.00, 1.03
	40–64	1.03 ^b	1.01, 1.06	1.00	0.97, 1.03	0.98 ^c	0.95, 1.02	1.01 ^c	1.00, 1.03
	65+	1.01	0.97, 1.05	0.98	0.93, 1.04	0.98	0.92, 1.05	1.00 ^c	0.97, 1.04
SO ₂	0–4	1.00 ^b	1.00, 1.01	0.99	0.93, 1.04	1.00	0.99, 1.01	1.00	1.00, 1.01
	5–18	1.00 ^b	1.00, 1.01	1.03	0.98, 1.09	1.03 ^b	1.01, 1.04	1.01	1.00, 1.01
	19–39	1.00	0.99, 1.01	1.01	0.96, 1.07	0.97 ^c	0.96, 0.99	1.00	0.99, 1.01
	40–64	1.00	0.99, 1.01	0.97	0.92, 1.02	1.00	0.98, 1.02	1.00	0.99, 1.01
	65+	0.99	0.98, 1.01	1.06	0.97, 1.16	1.00	0.96, 1.04	0.99	0.98, 1.01
PM _{2.5}	0–4	1.01	0.99, 1.03	0.98	0.94, 1.02	1.02 ^b	1.00, 1.03	1.01 ^b	1.00, 1.02
	5–18	1.03 ^b	1.01, 1.05	0.99	0.95, 1.03	1.03 ^b	1.01, 1.06	1.02 ^b	1.01, 1.04
	19–39	1.01 ^b	1.00, 1.03	1.02	0.98, 1.06	0.99	0.96, 1.01	1.00 ^c	0.99, 1.02
	40–64	1.02 ^b	1.00, 1.04	1.00	0.96, 1.04	1.00	0.97, 1.03	1.01	0.99, 1.02
	65+	1.04 ^b	1.00, 1.08	0.93	0.87, 1.00	1.01	0.96, 1.06	1.02	0.99, 1.05

^aStandard units: 28 p.p.b. for O₃, 0.5 p.p.m. for CO, 12 p.p.b. for NO₂, 5 p.p.b. for SO₂, and 8 µg/m³ for PM_{2.5}. ^bSignificant at the $\alpha=0.05$ level. ^cSignificantly different from 5 to 18 age group.

daily counts were highest in the 5–18 year age group, followed by the 0–4 year age group, in all cities (Table 2). Males had approximately twice the mean daily counts of females in the younger age groups (0–4 and 5–18 years); in the older age groups this pattern reversed to females having about twice as many mean daily visits as males in all three cities. Non-whites had more mean daily visits than whites in the younger age groups, and had similar mean daily visits in the older age groups.

Rate ratios and corresponding 95% confidence intervals for city-specific and weighted average associations can be found in Table 3. Comparing the weighted average results across age groups, associations between pollutant concentrations and asthma ED visits were strongest in the 5–18 year age group for all pollutants. For O₃, for example, the RR per 28 p.p.b. was 1.07 (95% confidence interval (CI): 1.04, 1.10) in the 5–18 year olds compared with a significantly weaker, though statistically significant positive, association of 1.03 (CI: 1.01, 1.05) in the 0–4 year olds and significantly weaker and non-significant associations in the adult age groups with RRs per 28 p.p.b. of 1.03 (CI: 1.00, 1.05) in 19–39 year olds, 1.01 (CI: 0.98, 1.04) in 40–64 year olds, and 1.03 (CI: 0.97, 1.09) in those 65 years and older. Similar patterns of associations across age groups were found for CO and NO₂, with strongest weighted average associations observed for the 5–18 year age group (RRs of 1.03 (CI: 1.02, 1.05) per 0.5 p.p.m. CO and 1.05 (CI: 1.04, 1.07) per 12 p.p.b. NO₂) and significantly weaker, but statistically significant, positive associations in the 0–4 year age group. Associations in the adult age groups for CO and NO₂ were significantly weaker than those in the 5–18 year old group and generally non-significant. For SO₂ and PM_{2.5}, associations with asthma ED visits were weaker overall compared with O₃, CO, and NO₂; however, the pattern of the 5–18 year old age group having the highest RRs remained, with RRs in the 5–18 year olds of 1.01

(CI: 1.00, 1.01) per 5 p.p.b. SO₂ and 1.02 (CI: 1.01, 1.04) per 8 µg/m³ PM_{2.5}.

Sensitivity analyses on model specification showed similar results for a wide range of degrees of freedom for both the temperature and time splines. In general, air pollution–asthma associations from models controlling for maximum temperature (using the same specifications as used for minimum temperature in our main models) were similar to those controlling for minimum temperature (i.e., our main models). However, in Atlanta the use of maximum temperature attenuated the association between O₃ and asthma ED visits, particularly among the younger age groups (0–4, 5–18, and 19–39 years). This attenuation was more substantial as the degrees of freedom in the time spline were increased, and may be attributed to over control. Ozone formation is highly sensitive to temperature, and the Pearson correlation between 3-day moving average ozone and maximum temperature was 0.72 compared with a lower correlation of 0.60 between ozone and minimum temperature in Atlanta where both temperature variables are represented as specified in our main model — lag 0 temperature plus 2-day moving average (of the previous day and 2 days prior).

The observed trend of 5–18 year olds having the highest combined RRs, followed by 0–4 year olds generally persisted in the sub-analyses by sex and race (Supplementary Table 1). Figures 1–5 illustrate the pattern of combined RRs and corresponding 95% CIs for each pollutant (axes vary by pollutant for better visualization of the results). However, the higher RRs in the 5–18 year age group for all pollutants, particularly for O₃ and NO₂, appeared to be partially driven by high RRs in non-whites. Considering the weighted average results for 5–18 year olds, associations of O₃ and NO₂ among non-whites (RRs of 1.15 (1.11, 1.19) per 28 p.p.b. O₃ and 1.09 (1.06, 1.11) per 12 p.p.b. NO₂) were

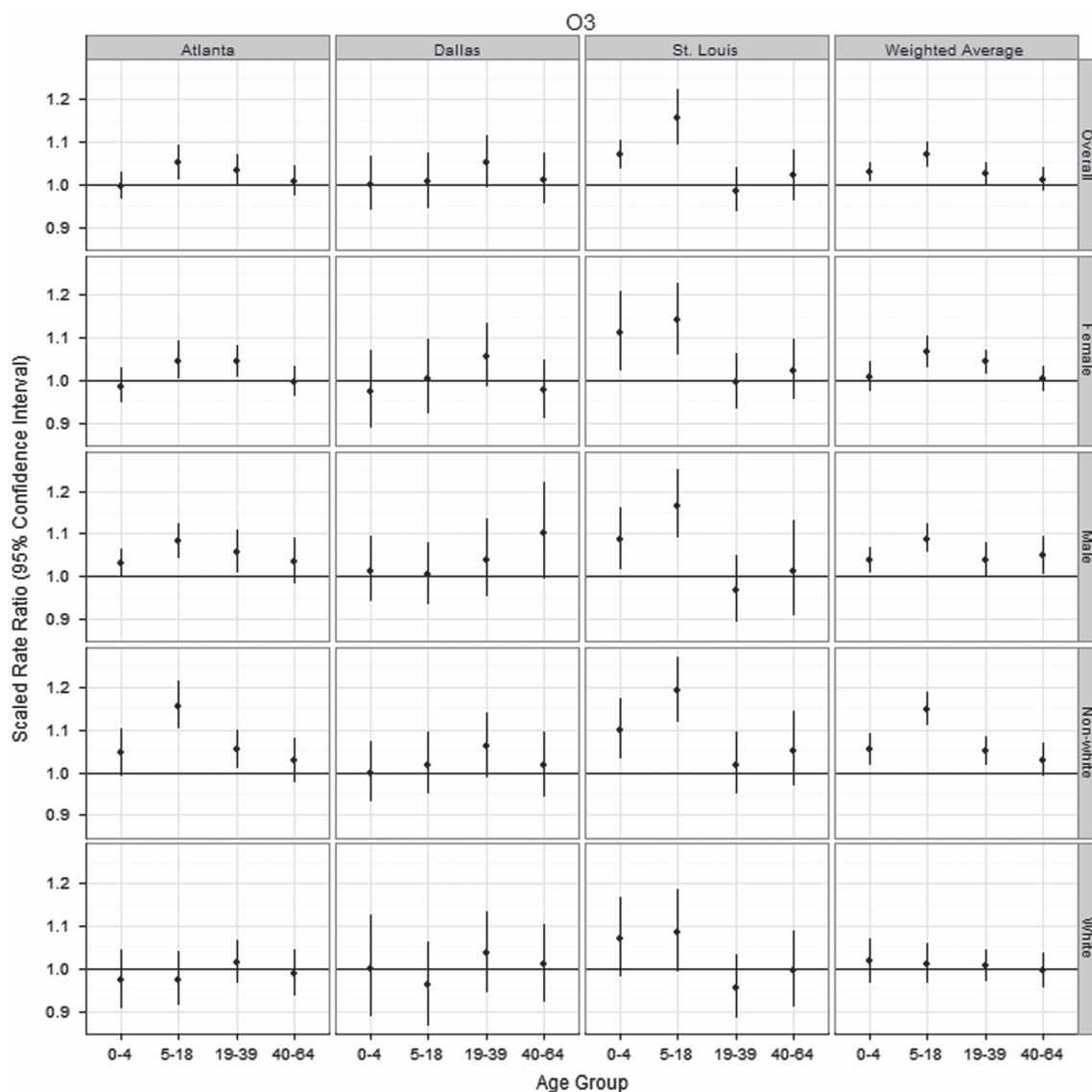


Figure 1. Rate ratios for the association between a standard unit increase in 3-day moving average O₃ concentrations and asthma ED visits in Atlanta (1993–2009), Dallas (2006–2009), and St. Louis (2001–2007) by gender and race (the 65+ age group was removed due to imprecision of results; standard units: 28 p.p.b. for O₃, 0.5 p.p.m. for CO, 12 p.p.b. for NO₂, 5 p.p.b. for SO₂, and 8 µg/m³ for PM_{2.5}).

significantly stronger (2-sided $P < 0.001$, $P < 0.001$, respectively) than among whites (RRs of 1.01 (0.96, 1.06) per 28 p.p.b. O₃ and 1.02 (1.00, 1.05) per 12 p.p.b. NO₂). In addition, associations in the 5–18 year old age group were generally stronger among males than females; this was particularly observed for CO and NO₂ with associations among males (RRs of 1.05 (1.03, 1.06) per 0.5 p.p.m. CO and 1.07 (1.05, 1.09) per 12 p.p.b. NO₂) significantly stronger (2-sided $P = 0.010$, $P = 0.008$, respectively) than among females (RRs of 1.01 (0.99, 1.03) per 0.5 p.p.m. CO and 1.03 (1.01, 1.06) per 12 p.p.b. NO₂). No significant differences in associations between the demographic sub-groups were observed for SO₂ and PM_{2.5}, although patterns of weighted average associations by sex and race across age groups were generally similar to the other pollutants with weaker associations overall. The overall trends observed in the sub-analyses appeared to be driven mainly by the city-specific results from Atlanta and St. Louis; the power of the Dallas analyses was limited by the short study period.

DISCUSSION

This multi-city study found consistent positive associations between short-term concentrations of ambient O₃, CO, NO₂, and PM_{2.5} and asthma ED visits among children under the age of 19, with strongest associations observed for 5–18 year olds compared with younger and older age groups. These results are similar to those found elsewhere. In a study of eight cities in Korea, children under 15 years old were more likely than older age groups to be hospitalized for asthma when concentrations of O₃, NO₂, and PM₁₀ were higher.⁶ Likewise, short-term increases in ambient PM_{2.5} and O₃ concentrations were also associated with an elevated risk of asthma-related hospitalization among 6–18 year olds in New York City.⁵ A study on ED visits for asthma in an industrial Canadian city found stronger associations with increases in O₃, CO, NO₂, and SO₂ for children between 2 and 14 than for adults.⁴

Our results of strong associations in the pediatric groups may be related to several well-documented susceptibility factors

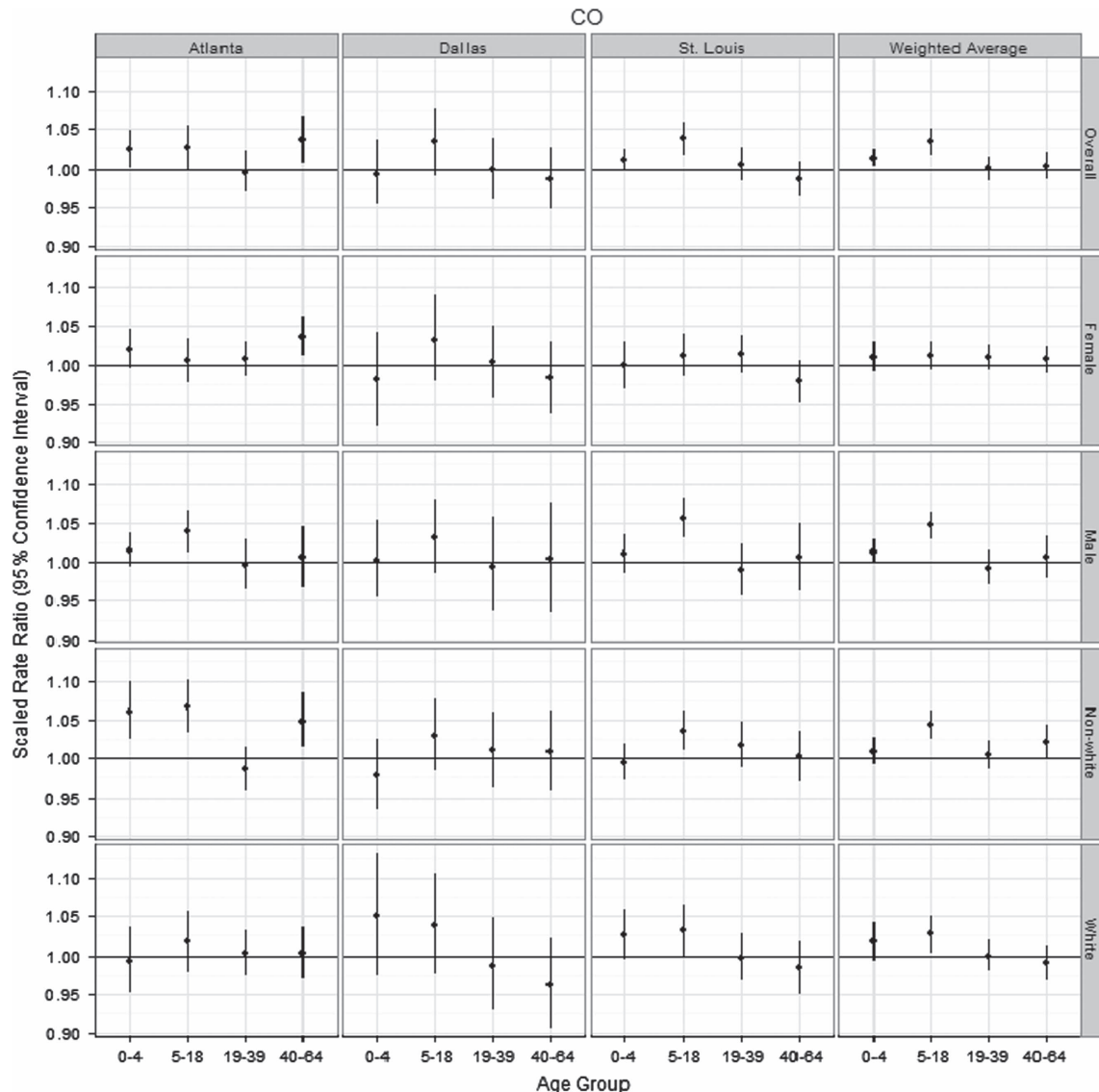


Figure 2. Rate ratios for the association between a standard unit increase in 3-day moving average CO concentrations and asthma ED visits in Atlanta (1993–2009), Dallas (2006–2009), and St. Louis (2001–2007) by gender and race (the 65+ age group was removed due to imprecision of results; standard units: 28 p.p.b. for O_3 , 0.5 p.p.m. for CO, 12 p.p.b. for NO_2 , 5 p.p.b. for SO_2 , and $8 \mu g/m^3$ for $PM_{2.5}$).

experienced by children. For example, children may be more susceptible to harmful effects of air pollution because their less-developed respiratory system may become more obstructed when exposure to air pollution causes inflammation in their smaller airways. Children also have less developed immune systems than adults, higher ventilation rates, and higher air pollution exposures per body weight than adults, which may increase the severity of the effects of pollutant exposure.^{12–14} Children may also experience higher levels of exposure to ambient air pollution than adults because they are more physically active and spend more time outside, thus increasing the frequency and duration of their exposure.¹¹

We also examined sex and race as potential factors explaining observed age-related differences in air pollution–asthma associations. The pattern of strong associations among 5–18 year olds appeared to be partially driven by non-white and male patients. For example, non-whites appeared to be more vulnerable to short-term increases in ambient pollution, particularly O_3 and NO_2 , than whites in the 5–18 year old age group.

A study in Phoenix found that both black and Hispanic children (0–14 years old) had stronger associations between NO_2 concentrations and asthma hospitalization than white children.²⁴ Other studies have found effect modification by race for O_3 and $PM_{2.5}$. Strickland et al.²⁵ found that children aged 2–16 with African American mothers had greater susceptibility to effects of O_3 on asthma ED visits than children with white mothers. Similarly, a study of children in Texas found that African-American and Hispanic children had a stronger association between increases in ambient O_3 and initial asthma diagnosis than white children.²⁶ A national study found that African-American adults had a stronger association between asthma attacks and $PM_{2.5}$ concentrations than white adults.²⁷ Racial and ethnic minorities may be overall more susceptible to asthma exacerbations in response to asthma triggers as several studies have found that African Americans and Hispanics of all ages have more poorly controlled asthma than whites and that this pattern persists even in high income groups.^{28–30}

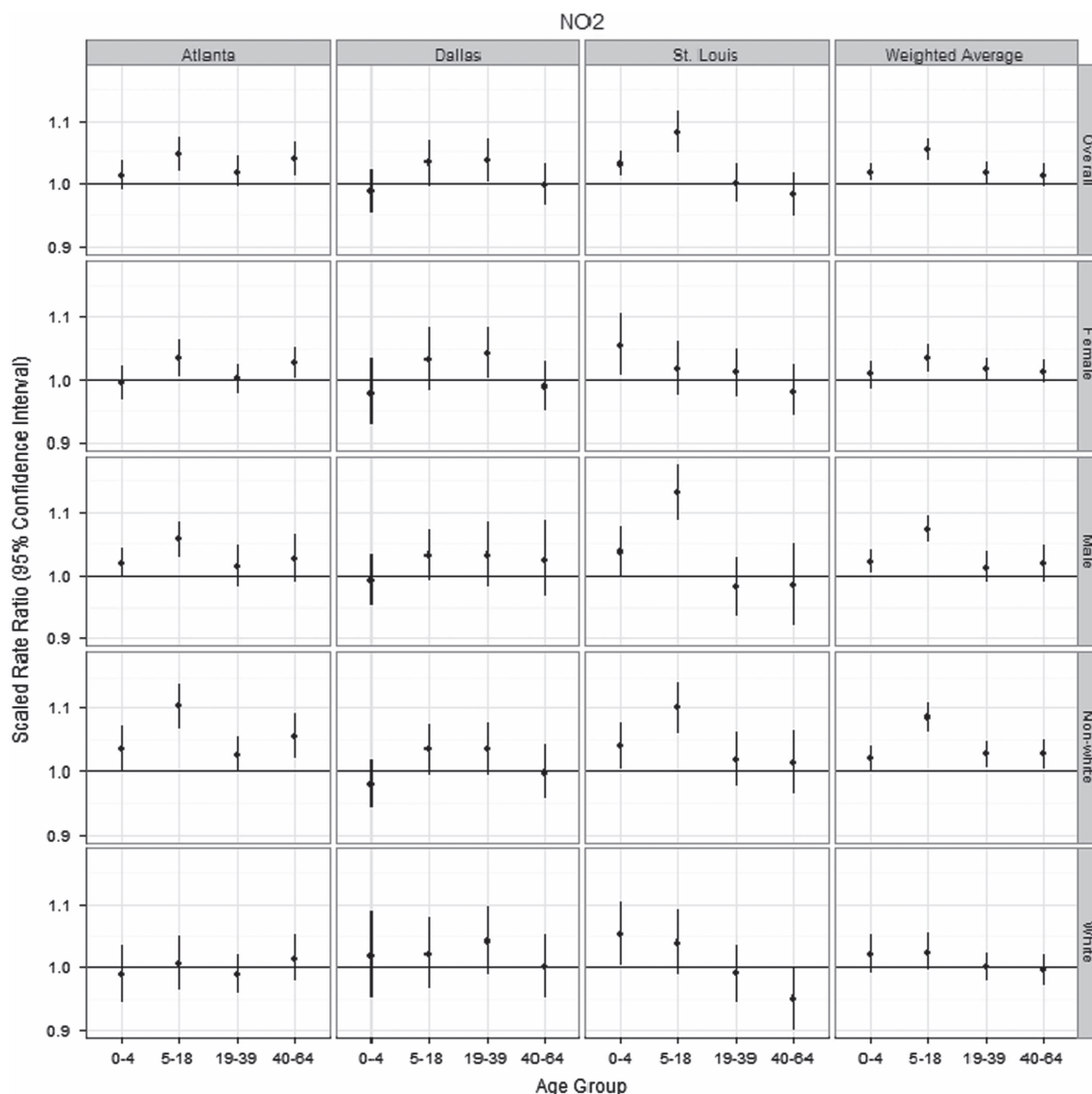


Figure 3. Rate ratios for the association between a standard unit increase in 3-day moving average NO_2 concentrations and asthma ED visits in Atlanta (1993–2009), Dallas (2006–2009), and St. Louis (2001–2007) by gender and race (the 65+ age group was removed due to imprecision of results; standard units: 28 p.p.b. for O_3 , 0.5 p.p.m. for CO, 12 p.p.b. for NO_2 , 5 p.p.b. for SO_2 , and $8 \mu\text{g}/\text{m}^3$ for $\text{PM}_{2.5}$).

Considering stratification by sex, associations between asthma ED visits and ambient air pollutant concentrations were generally stronger among males than females in the 5–18 year old age group, with significant differences observed for CO and NO_2 . Pediatric males may spend more time outside (e.g., playing on sports teams) than females, which would lead to increased exposure. These results by sex are similar to those by Son *et al.*,⁶ who found that males had higher risk ratios between asthma hospitalizations and CO and NO_2 than females; however, their results were not statistically significant. A study in Toronto did not find any significant differences in the associations between asthma hospitalizations and $\text{PM}_{2.5}$ concentrations by sex among children 6–12 years old.¹⁷ Overall, few studies have examined modification of the effects of ambient air pollution on asthma by sex, thus this may be a topic for further investigation.

There are several limitations to our study. First, our epidemiologic results may be impacted by potential measurement error in our exposure data. We attempted to limit this measurement error by calculating population-weighted averages of air pollution concentration data available from multiple monitoring sites in

each city on each study day. This ensures the daily pollution values used in our epidemiological models represent population exposures to ambient concentrations better than those from single fixed-site monitors. It is important to note, however, that the population-weighted average concentrations were weighted with overall population counts across each study area, not age-specific population counts, and thus our age-specific RRs may be impacted by differential measurement error. Second, asthma ED visits were identified only using primary ICD-9 code information. Not including visits with asthma listed in secondary ICD-9 codes may have reduced our sample size and thus the power of the study. However, since asthma listed in secondary codes indicates co-occurrence with other morbidities that in some cases may be the main reason for the ED visit, using secondary ICD-9 code information to identify asthma visits may result in a non-specific case definition and attenuate the apparent association between pollutant concentrations and health-care visits. Third, Atlanta was missing a large amount of race data in the demographic sub-analyses. The impact of the missing data on the results is difficult to quantify; however, there was some consistency across cities in

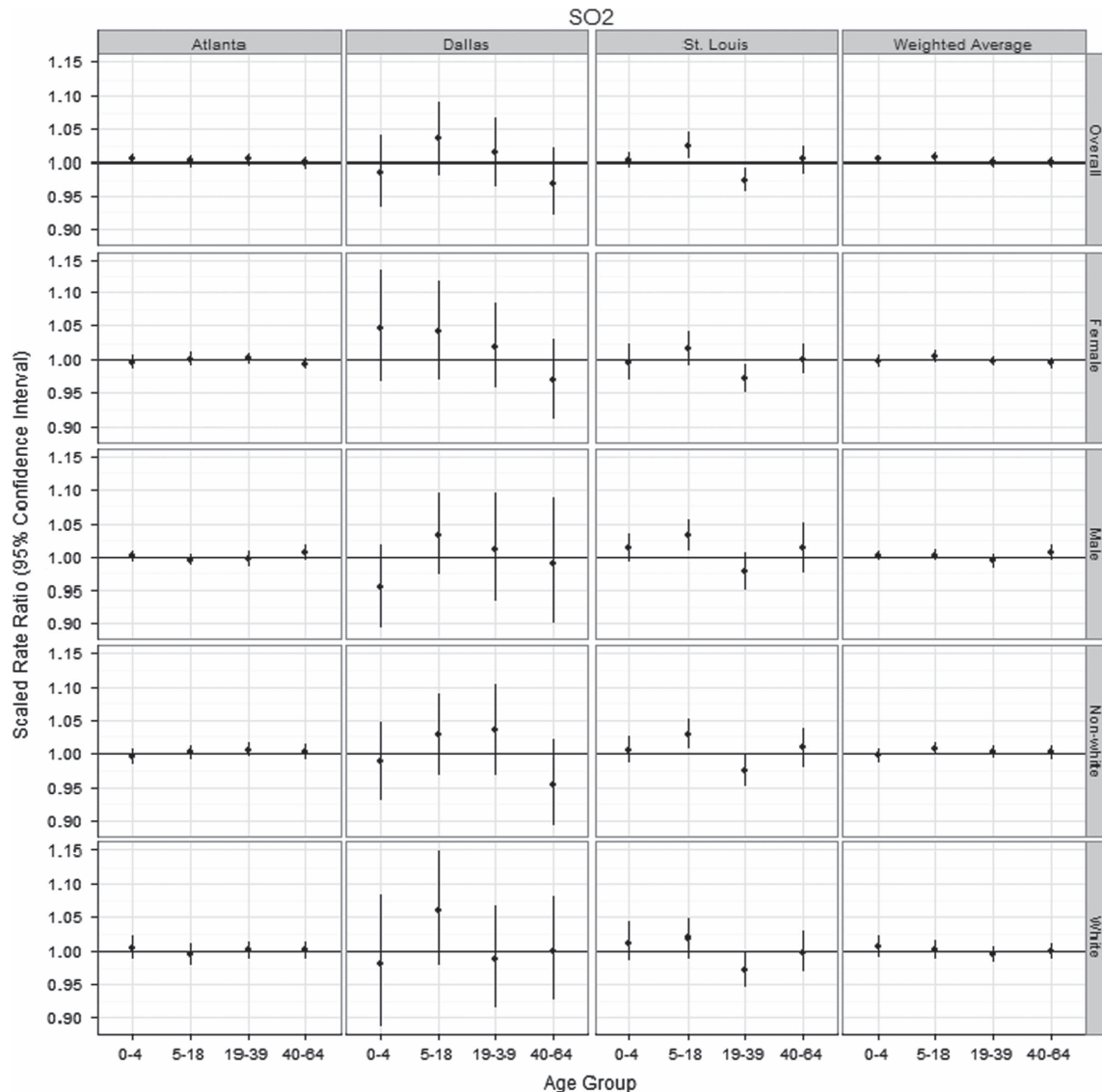


Figure 4. Rate ratios for the association between a standard unit increase in 3-day moving average SO_2 concentrations and asthma ED visits in Atlanta (1993–2009), Dallas (2006–2009), and St. Louis (2001–2007) by gender and race (the 65+ age group was removed due to imprecision of results; standard units: 28 p.p.b. for O_3 , 0.5 p.p.m. for CO, 12 p.p.b. for NO_2 , 5 p.p.b. for SO_2 , and $8 \mu\text{g}/\text{m}^3$ for $\text{PM}_{2.5}$).

the race sub-analyses, which provides some reassurance that in Atlanta we captured accurate patterns of associations across race sub-groups. Finally, sub-analyses were limited to race and sex; there may be other unmeasured factors that differed across age groups that might explain further observed age-related differences in air pollution–asthma associations.

In summary, our results suggest that children with asthma are disproportionately affected by acute changes in ambient air pollution, compared with adults; this may be particularly explained by stronger risks faced by non-white and male populations in this age group. This study supports the consideration of children as a susceptible group when the Environmental Protection Agency sets National Ambient Air Quality Standards for O_3 , CO, NO_2 , SO_2 , and $\text{PM}_{2.5}$ to protect public health.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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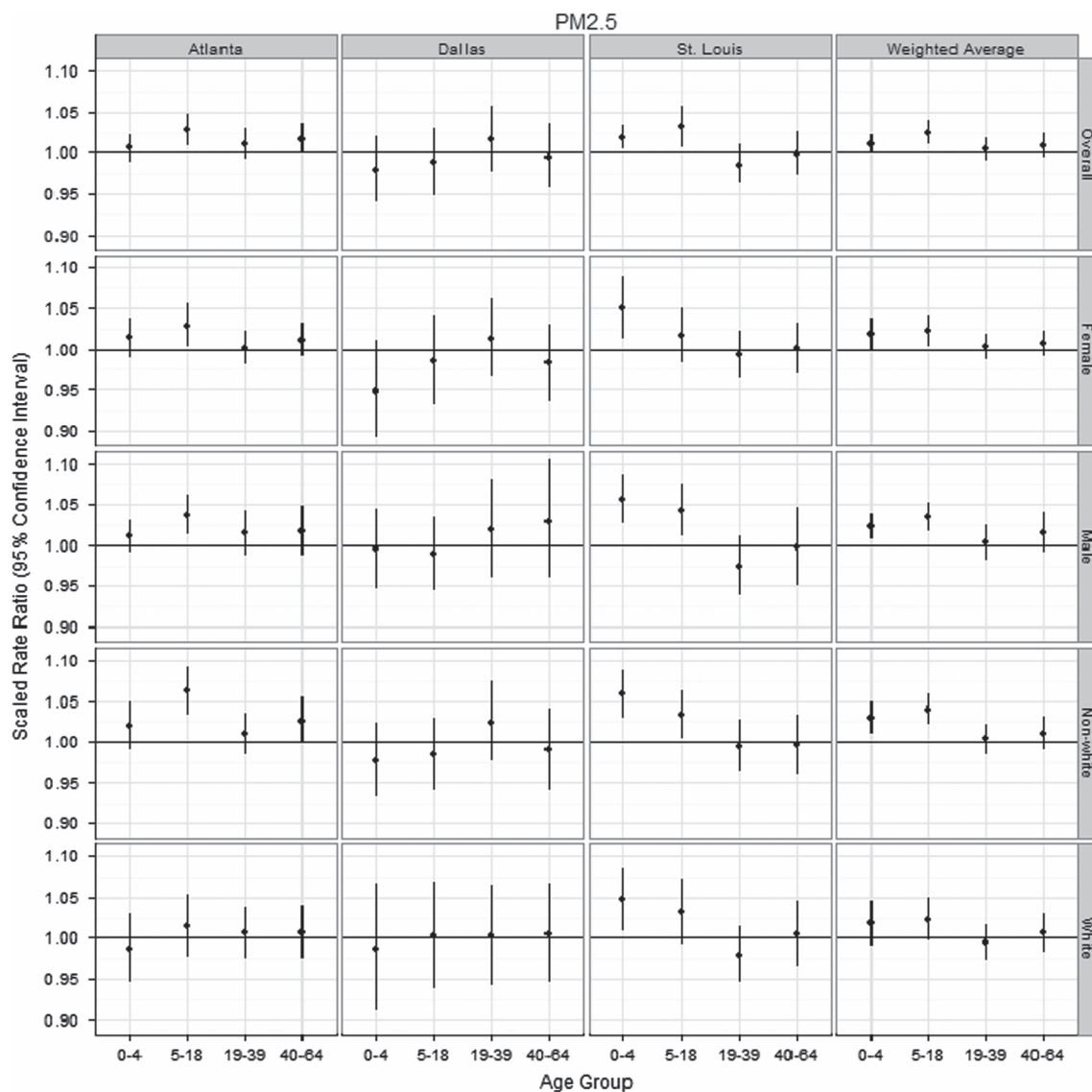


Figure 5. Rate ratios for the association between a standard unit increase in 3-day moving average $PM_{2.5}$ concentrations and asthma ED visits in Atlanta (1993–2009), Dallas (2006–2009), and St. Louis (2001–2007) by gender and race (the 65+ age group was removed due to imprecision of results; standard units: 28 p.p.b. for O_3 , 0.5 p.p.m. for CO, 12 p.p.b. for NO_2 , 5 p.p.b. for SO_2 , and $8 \mu g/m^3$ for $PM_{2.5}$).

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Supplementary Information accompanies the paper on the Journal of Exposure Science and Environmental Epidemiology website (<http://www.nature.com/jes>)