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Short-term exposure to air pollution and mental disorders: a case-crossover study in New York City

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Abstract

There is growing evidence suggesting that exposure to air pollutants is associated with mental disorders. We investigated the impact of short-term exposures to both fine particulate matter ($PM_{2.5}$) and ozone (O_3) assessed at fine spatiotemporal resolutions on emergency room (ER) visits related to mental disorders using 475 755 records from New York City between 2010 and 2016. We assessed the short-term impact of daily air pollution exposure on ER visits using a case-crossover design with conditional logistic regression. We further tested whether the impact of $PM_{2.5}$ and O_3 varied by individuals' age, sex, and race/ethnicity, and if associations were modified by the degree of visibility of greenspace at individuals' residences. Results suggested that the relative risk of visiting an ER for mental-disorders increased by 2.78% (95% CI: 1.82%–3.76%) with a 10 $\mu g\,m^{-3}$ increase in ambient $PM_{2.5}$ concentration over a 4 day (d) moving average (lag 0–3 d) and increased by 0.71% (95% CI: 0.28%–1.15%) with a 10 ppb increase in O_3 concentration on a single day lag (lag 1 d), and that these effects were modified by age and race/ethnicity, but not by sex or surrounding greenery. Specifically, we found that age group 19–35 years old and non-Whites were more susceptible to the effects of ambient air pollution exposure. In terms of specific disorders, we found that both $PM_{2.5}$ and O_3 have an effect on ER visits for psychotic disorders, but not dementia. Our findings suggest that short-term exposure to ambient air pollution is associated with increased ER visits for mental disorders. Further research is needed to determine the underlying mechanisms by which exposure to $PM_{2.5}$ and O_3 is linked to these ER visits.

1. Introduction

A meta-analysis of global epidemiological studies found that 17.6% of respondents met criteria for a mental disorder in the preceding 12 months, whereas 29.2% met criteria at some point in their lifetimes (Steel *et al* 2014). Although substantial advances have been made in research focusing on clinical and pharmacological/psychosocial interventions to prevent and treat common mental disorders, our understanding of risk and protective factors for these conditions remains incomplete. Despite a long-standing interest in the role of psychosocial environmental factors, such as stressful life events and social support (Brown and Harris 1989, Maulik *et al* 2010), the potential role of the physical environment has gained attention only recently (Basu *et al* 2018, Chen *et al* 2018, Liu *et al* 2021, Yoo *et al* 2021, Zhang *et al* 2021).

In terms of the physical environment, there is growing evidence suggesting that exposure to air pollutants is associated with increases in emergency room (ER) visits for mental disorders. For example, Szyszkowicz *et al* (2009, 2016, 2018), Cho *et al* (2014), Oudin *et al* (2018), Brokamp *et al* (2019) and Thilakaratne *et al* (2020) found that short-term exposure to air pollution increased the frequency of

ER visits related to mental disorders, whereas other studies (Power *et al* 2015, Kim *et al* 2016, Pun *et al* 2017, Vert *et al* 2017) found that long-term exposure of air pollution is associated with mental illness. However, several studies have failed to find a statistically significant association between fine particulate matter ($PM_{2.5}$) and mental disorder related health outcomes (Wang *et al* 2014b, Chen *et al* 2018, Li *et al* 2020). Similarly, inconsistent findings were reported about ozone (O_3) as some studies (Szyszkowicz 2007, Lim *et al* 2012, Nguyen *et al* 2021) found positive and significant associations between O_3 and mental disorders and others found no associations (Wang *et al* 2014b, Oudin *et al* 2018). Such inconsistent findings across studies on the effects of $PM_{2.5}$ and O_3 exposures might be related to these studies relying on city-wide average air pollutant concentration estimates based on fixed monitoring stations. These city-wide averages fail to account for the spatial variation in pollutants across the neighborhoods within cities. As is recognized by many (Chen *et al* 2018, Song *et al* 2018, Bai *et al* 2020, Li *et al* 2020, Lowe *et al* 2021), fixed monitoring station-based exposure estimation cannot provide accurate exposure to $PM_{2.5}$ or O_3, and thus likely leads to exposure misclassification. Moreover, previous studies mainly used city-level time-series or cross-sectional designs, which suffer from ecological bias and yield findings that are not directly applicable to individual level (Brokamp *et al* 2019).

Additionally, the mixed results potentially imply the role of other variables that modify the impact of air pollution on mental health outcomes. For example, some studies have found that the effects of air pollution exposure on mental health vary by season, as well as by individuals' age, sex, and race/ethnicity (Chen *et al* 2018, Li *et al* 2020, Lu *et al* 2020, Thilakaratne *et al* 2020, Lowe *et al* 2021). A recent cross-sectional study in the Netherlands by Klompmaker *et al* (2019) has also shown that individuals' surrounding greeneries were associated with decreased psychological distress, whereas a related study by Yoo *et al* (2022) in New York City (NYC) found that the effect of greenspace exposure on mental health can be moderated by the socioeconomic conditions of the neighborhoods in which individuals reside. Lastly, mixed results from previous studies might be related to the nature of the particular mental disorders represented in these studies. For example, both Gao *et al* (2017) and Lu *et al* (2020) found no significant associations between $PM_{2.5}$ exposure and total mental disorders, although they found significant associations with specific mental disorders, such as schizophrenia, mood disorders, and anxiety. These previous studies raise the possibility that the effects of short-term air pollution exposure on mental health might vary not only by individuals' demographic characteristics, but also by where they live and

the surrounding greenery that they are exposed to and the specific type of mental disorder.

The present study was designed to investigate the impact of short-term exposure to daily ambient $PM_{2.5}$ and O_3 assessed at fine spatial resolutions (i.e. 1 km or less) on ER visits related to mental disorders using a case-crossover design. In addition to examining the impact of acute $PM_{2.5}$ and O_3 exposure on ER visits related to mental disorders as a whole, we also examined the risk of ER visits for specific mental disorders. We further tested whether the impact of $PM_{2.5}$ and O_3 varied by individuals' age, sex, and race/ethnicity, and if the associations are modified by the degree of visibility of greenspace at individuals' residence.

2. Methods

2.1. Study area and participant
The study area encompassed the five boroughs in NYC: the Bronx, Brooklyn, Manhattan, Queens, and Staten Island. We obtained data on daily ER visits from the Statewide Planning and Research Cooperative System (SPARCS) operated by New York State Department of Health. SPARCS is a comprehensive all payer data reporting system that collects information on discharges from hospitals and outpatients. In the present study, we used ER visit data (for outpatient care only) of daily records from 1 January 2010 to 31 December 2016. These data include information on admission date, discharge date, date of birth, street address of residence and demographic information (age, sex, and race/ethnicity). Any record with a missing or incomplete address was excluded from the study. For the records with full addresses, we geocoded their residence using ArcGIS (version 10.8.1) and applied a multi-step procedure to validate geocoding results.

In this study, we identified daily visits for mental disorders based on the primary diagnosis code using the International Classification of Disease, Ninth Revision (ICD-9: 290–319) and Tenth Revision (ICD-10: F00–F99). We also classified mental disorders into five specific diseases: psychoactive substance use (ICD9: 291 292, 303–305; ICD10: F10–F19), psychotic disorders (ICD9: 295, 297, 298.1–298.9, 301.2; ICD10: F20–F29), mood disorders (ICD9: 296, 298, 300.4, 311; ICD10: F30–39), anxiety disorders (ICD9: 298.2, 300, 306, 307.8, 308, 309, 310.8; ICD10: F40–49), and dementia (ICD9: 290, 294.1, 294.2; ICD10: F00–F03). Our grouping and selection of records were largely based on published studies (Khalaj *et al* 2010, Williams *et al* 2012, Wang *et al* 2014a, Trang *et al* 2016, Almendra *et al* 2019).

2.2. Environmental exposure assessment
We estimated 1×1 km^2 gridded daily mean temperature for NYC during the study period (2010–2016)

using a similar approach described by Jin *et al* (2022). Essentially, we used a random forest model to estimate daily mean air temperatures from the 1×1 km^2 daily nighttime mean surface temperatures (Ts) retrieved from the Moderate Resolution Imaging Spectroradiometer (MODIS) MOD11A1 product. Adjusted predictors included land cover type, normalized difference vegetation index, and elevation. Nighttime Ts was chosen as the main predictor and missing values were filled using the fifth generation of European Center for Medium-Range Weather Forecasts atmospheric reanalysis (ERA5-land reanalysis) dataset (Muñoz Sabater 2019, Jin *et al* 2022). The model performance was assessed using a 10-fold cross-validation by year at grid cells where monitors were located, and yielded the total, temporal, and spatial R^2 of 0.977, 0.978, and 0.945 and the root mean square error of 1.552 °C, 1.473 °C, and 0.470 °C, respectively. The dew point temperature data were obtained at a resolution of 0.1 ° ($\approx 10 \times 10$ km) during 2010–2016 from the ERA5-land reanalysis of the global climate (Muñoz Sabater *et al* 2021).

We used 1×1 km^2 gridded daily PM$_{2.5}$ and O$_3$ data for NYC during 2010–2016 from an ensemble-based model, which integrated three machine learning algorithms (specifically neural network, random forest, and gradient boosting) and had good performance with a 10-fold cross-validated R^2 of 0.86 and 0.90 for PM$_{2.5}$ and O$_3$ predictions, respectively (Di *et al* 2019, Requia *et al* 2020).

As a refined green space exposure metric, we quantified the visibility of street greenery from a pedestrian's perspective using geo-tagged Google Street View images, which is referred to as the green view index (GVI). Because the Google Street View images have similar view angles of pedestrians and are directly related to human perception of the surrounding environments, the GVI is likely to be more reflective of individuals' daily greenspace exposure than other metrics, such as proximity to greenspace (e.g., parks, gardens, and playgrounds) or neighborhood average of normalized difference vegetation indices (NDVI) derived from satellite images (Li *et al* 2015).

The details on the calculation of the GVI can be found in Li (2021) and Yoo *et al* (2022), but in brief it was calculated on the dense sample points captured at every 50 m along the street using the multi-year Google Street View images and the state-of-the-art deep convolutional neural network algorithm (Li 2021). Although every sample point was captured over the period between 2014 and 2020, any given year only covered a portion of the study area. Consequently, we used the most recent GVI available for each sampling point. Based on point-level indicators of street greenery (i.e., GVI values), we created a continuous surface of GVI using an interpolation method based on Voronoi tessellation (Amenta *et al* 1998, O'Sullivan and Unwin 2003).

For individuals' environmental exposure assessment, we assigned the daily exposures (PM$_{2.5}$, O$_3$, temperature, dew point temperature, and GVI) to each participant based on their residential address.

2.3. Statistical analysis

Case-crossover analysis is widely used to estimate acute associations of time-varying exposures, including ambient air pollutant concentrations and extreme temperature, with daily mortality or morbidity in a particular geographic region (Janes *et al* 2005, Armstrong *et al* 2014). Given a sample of subjects who experienced the event ('case'), exposure associated with the event is compared with exposure at 'control' (or 'referent') times. Because the case-crossover design makes within-subject comparisons, time-independent confounders (e.g. socio-economic conditions, pre-existing health conditions) are well controlled, but also the effects of time-dependent confounders can be effectively controlled by design if the referent times are matched with index time with respect to time-dependent confounders (e.g., the referent time periods are restricted to the same season).

In the present study, we used a case-crossover design with a conditional logistic regression model to estimate the association between environmental exposure and mental disorder-related ER visits. For each individual, the degree of PM$_{2.5}$ and O$_3$ exposures on the day when the individual visited the ER for mental disorders ('case' day) was compared with the exposure estimates on the other days before and after the visit (the same day of week in one and two weeks prior to and after the ER visit), referred to as 'control' days hereafter. By selecting control days from the same day of week before and after the case day, we assessed the associations between changes in individuals' exposure to air pollutants (PM$_{2.5}$ and O$_3$) and their mental health outcomes while effectively controlling for long-term temporal trends, seasonality, day of the week, and potential time-invariant confounders, such as the individual's age, sex, and other fixed participant characteristics (Janes *et al* 2005, Carracedo-Martínez *et al* 2010).

In the conditional logistic regression model (see appendix C for the model specification), we investigated PM$_{2.5}$ and O$_3$ at both single day lags from the day of ER visit (lag 0) up to 6 d (lag 6) and moving average lags for the period up to 6 lagged days (lag 0–6). The four sets of measurements estimated for control days (one and two weeks before and after the ER visit) were also included. We further adjusted for potential time-varying confounders by using natural cubic splines with 6 degrees of freedom (df) for ambient daily temperature and 3 df for dew point temperature. To account for potential cumulative effects of ambient temperature and dew point temperature, we used 6 (lag 0–6) and 3 (lag 0–3) day moving averages, respectively.

Given that the greenspace exposure metric is time invariant, we did not adjust for GVI but rather assessed it as a potential effect modifier for the $PM_{2.5}$ and O_3 effect on mental health outcomes. Specifically, we assessed whether the association between $PM_{2.5}$ and O_3 exposure and mental disorder-related ER visits differ by varying levels of greenness at the participant's residence using stratified analyses by modeling the $PM_{2.5}$- and O_3-ER visits for mental disorder for each of the four quartiles of GVI in the study area. The four quartiles (0–25th, 25–50th, 50–75th, 75–100th percentile of GVI) were chosen based on a previous study (Qiu *et al* 2021), although we also assessed effect modification by high (>50th percentile) and low (⩽50th percentile) levels of greenspace exposure to ensure the robustness of our results.

We also conducted stratified analyses for $PM_{2.5}$ and O_3 exposure effects on ER visits for mental disorders to examine effect modification by sex (female and male), age groups (below 18 years old, 19–34 years old, 35–49 years old, 50–64 years old, and above 65 years old), and race/ethnicity (non-Hispanic Black (Black), non-Hispanic White (White), non-Hispanic Asian (Asian), and Hispanic).

The statistical significance of effect modification was tested by calculating the 95% confidence interval (95% CI) of the difference between the effect estimate within each pair of the subgroup as (Zeka *et al* 2006, Wang *et al* 2018b, Chen *et al* 2019):

$$95\% \text{ CI} = (\hat{Q}_1 - \hat{Q}_2) \pm 1.96\sqrt{(\hat{\sigma}_1^2 + \hat{\sigma}_2^2)}, \quad (1)$$

where $\hat{Q}_1, \hat{Q}_2$ denote the model coefficients in the conditional logistic regression model for sex, age group, and race/ethnicity, as well as GVI. The corresponding standard errors are denoted as $\hat{\sigma}_1^2, \hat{\sigma}_2^2$, respectively.

All statistical analyses were conducted in R software (version 4.0.2) using *survival* and *spline* packages to analyze conditional logistic regression models and *gstat* and *dismo* to reconstruct GVI surface.

3. Results

3.1. Summary of environmental variables and ER visits

A total of 457 755 ER visits were made due to mental health-related illnesses in NYC between 1 January 2010 and 31 December 2016. The characteristics of ER visits are summarized in Table 1. Most patients were 19–34 years of age (141 573, 31.03%), 35–49 years old (122 157, 26.80%) and 50–64 years old (97 761, 21.40%). Relatively smaller percentages of cases were aged 18 or younger (66 089, 14.56%) or 65 or above (28 303, 6.21%). The majority of visits (287 909, 63.06%) were by males. We also found that Black patients made 31.09% (141 498) of mental disorder visits, while 30.84% (140 715) were by White patients, 3.21% (14 614) by Asian patients, 18.37%

(83 800) by Hispanic patients, and 16.49% (75 256) by 'Others'. Regarding the specific type of mental disorders, ER visits related to psychoactive substance use were the most frequent (43.08%), followed by anxiety disorders (19.79%), mood disorders (17.64%), psychotic disorders (10.64%) and dementia (0.83%).

Air pollutant concentrations over the study area are summarized in Table 2. During the study period, the daily average of $PM_{2.5}$ was 8.85 $\mu g\,m^{-3}$ with a standard deviation of 8.65 $\mu g\,m^{-3}$ and the daily mean of O_3 was 37.10 ppb with a standard deviation of 10.62 ppb. The daily average temperature in the study region varied from −10.31 °C to 30.65 °C with a mean of 13.27 °C and a standard deviation of 8.67 °C. The spatial distribution of GVI ranged between 0.00 and 92.45 with the mean of 18.25 and a standard deviation of 15.37. The spatial distributions of air pollutants ($PM_{2.5}$ and O_3) and green view index are presented in Figure 1.

3.2. Statistical analyses

We determined the main lag for the subsequent analyses by examining the percent changes in RR of ER visits at both single lags and moving average lags over an extended period from the current day (i.e., the day of the ER visit) up to the previous 6 days. As shown in Figure A.1, the percent change in RR estimates of moving average lags were consistently higher than the single lags at a given lag day for $PM_{2.5}$, although the percent change in RR estimates of the single day lag (lag 1) and some moving average lags (e.g., lag 0–6) yielded high percent change of RR for O_3. However, when both $PM_{2.5}$ and O_3 were taken into simultaneously, we found that $PM_{2.5}$ at the accumulative lag 0–3 and O_3 at the single day lag (lag 1) yielded the highest percent change of RR. Thus, we considered the four day moving average (lag 0–3 d) and single day lag (lag 1) as the main lags for $PM_{2.5}$ and O_3, respectively.

Based on these main lags for $PM_{2.5}$ and for O_3, we estimated the RR for total mental disorders, as well as the specific mental disorders. The results summarized in Table 3 indicate that a 10 $\mu g\,m^{-3}$ increase in ambient $PM_{2.5}$ and 10 ppb increase in ambient O_3 exposure were respectively associated with 2.78% (95% confidence interval (CI): 1.82%–3.76%) and 0.71% (95% CI: 0.28%–1.15%) increased risk of having an ER visit related to any of the mental disorders examined in this study. We also found that higher $PM_{2.5}$ concentrations were associated with increased risk for ER visits related to substance abuse (RR = 2.82%; 95% CI: 1.36%–4.29%), anxiety disorders (3.25%; 95% CI: 1.07%–5.48%) and psychotic disorders (3.39%; 95% CI: 0.37%–6.49%), respectively. For O_3, we found that higher O_3 concentrations were associated with increased risk for ER visits related to mood disorders (1.38%; 95% CI: 0.33%–2.45%) and psychotic disorders (1.94%; 95% CI: 0.59%–3.32%)

Table 1. Characteristics of emergency room visits (New York City, 2010–2016).

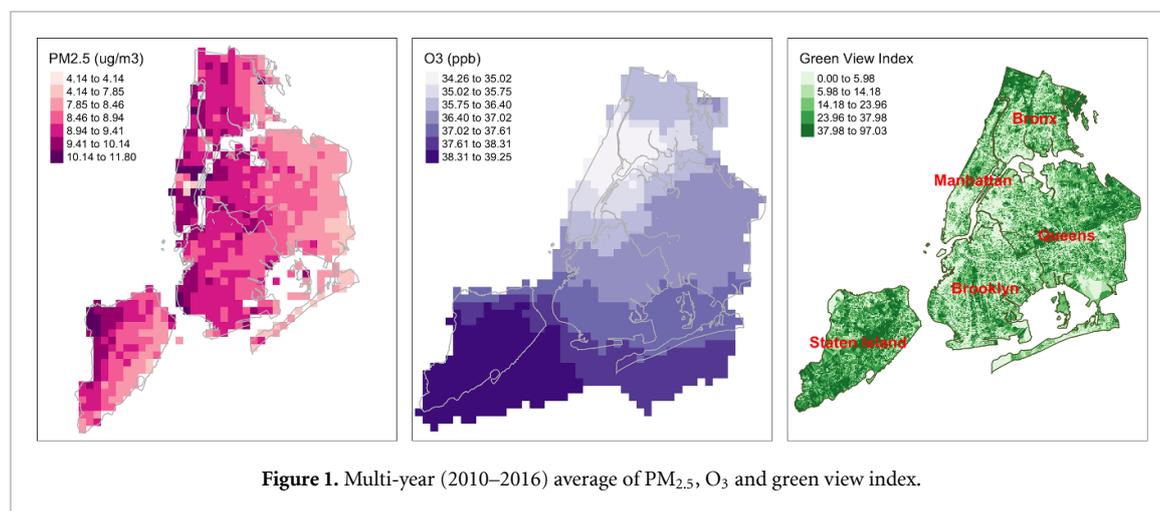| Characteristics	Total mental disorders	Substance abuse	Anxiety	Mood disorders	Psychotic disorders	Dementia
Total counts						
N	457 755	196 507	90 642	81 086	46 243	3816
Age group (%)						
0–18	14.56	3.72	17.73	22.57	4.15	0.08
19–34	31.03	29.78	36.55	32.32	35.34	0.31
35–49	26.80	32.47	24.07	24.30	30.43	1.21
50–64	21.40	29.33	14.91	16.31	23.54	9.30
above 65	6.21	4.69	6.73	4.51	6.53	89.10
Sex (%)						
Female	36.94	20.89	59.10	52.62	34.66	56.60
Male	63.06	79.11	40.90	47.38	65.34	43.40
Race/ethnicity (%)						
White	30.84	34.28	34.28	28.95	20.66	38.00
Black	31.09	26.02	27.67	31.35	49.06	32.63
Asian	3.21	2.75	3.97	3.53	3.37	3.77
Hispanic	18.37	18.65	18.42	19.91	13.35	13.84
Others	16.49	18.30	15.66	16.26	13.56	11.77

Table 2. Summary statistics of daily ambient $PM_{2.5}$, temperature and green view index (New York City, 2010–2016).

	Mean	SD	Min	Q_{25}	Median	Q_{75}	Max	IQR
$PM_{2.5}$ ($\mu g\,m^{-3}$)	8.85	8.65	0.00	4.90	7.42	11.32	99.06	6.42
O_3 (ppb)	37.10	10.62	13.50	29.14	35.44	44.05	78.34	14.91
Temperature (°C)	13.27	8.67	−10.31	5.23	13.39	20.63	30.65	15.40
Dew point temperature (°C)	6.46	10.31	−28.14	−1.13	7.77	15.33	24.62	16.46
Green view index	18.25	15.37	0.00	6.08	14.05	26.76	92.45	20.69

SD: standard deviation.

Q_{25}, Q_{75}: the first and the third quartiles.

IQR: inter quartile range (Q_{75}–Q_{25}).

Figure 1. Multi-year (2010–2016) average of $PM_{2.5}$, O_3 and green view index.

Results of the subgroup analyses are summarized in Table 4, revealing that the exposure to ambient $PM_{2.5}$ was associated with ER visits related to mental disorders in all age group except 35–49 years old. The age group 19–34 was also statistically significant associated with exposure to ambient O_3. In terms of race/ethnicity, the RRs associated with the increased ambient $PM_{2.5}$ were statistically significant for Black (2.80%; 95% CI: 1.05–4.58), Hispanic (5.35%; 95% CI: 3.07–7.68), and Others (2.58%; 95% CI: 0.27–4.94), but not for Whites and Asians. Furthermore, Whites were significantly less susceptible to the effects of $PM_{2.5}$ than each of other race/ethnicity groups (p-values $\leqslant$ 0.014).

We found no evidence of effect modification by greenspace exposure quantified as GVI. The results are summarized in Table B.1. The effect estimates of $PM_{2.5}$ and O_3 on ER visits related to mental disorders were similar at different levels (four quartiles) of greenspace exposure. Substantively identical results

Table 3. Percent changes in RR of ER visits for mental disorders at the extended lag period (lag 0–3 for $PM_{2.5}$, lag 1 for O_3).

Outcomes	$PM_{2.5}$	O_3
All mental disorders	2.78 (1.82, 3.76)	0.71 (0.28, 1.15)
Substance abuse disorders	2.82 (1.36, 4.29)	0.4 (−0.24, 1.05)
Anxiety disorders	3.25 (1.07, 5.48)	0.53 (−0.44, 1.51)
Mood disorders	2.08 (−0.21, 4.42)	1.38 (0.33, 2.45)
Psychotic disorders	3.39 (0.37, 6.49)	1.94 (0.59, 3.32)
Dementia	3.59 (−6.3, 14.53)	2.27 (−2.25, 6.99)

Table 4. Percent changes in RR of ER visits for total mental disorders by subgroups at the extended lag period (lag 0–3 d for $PM_{2.5}$ and lag 1 d for O_3).

	$PM_{2.5}$	O_3
Sex		
Female	2.49 (0.91, 4.10)	1.03 (0.32, 1.75)
Male	2.95 (1.74, 4.18)	0.53 (0.00, 1.08)
Age group		
0–18	4.11 (1.58, 6.71)	0.59 (−0.58, 1.78)
19–34	2.71 (0.98, 4.46)	1.68 (0.91, 2.46)
35–49	1.19 (−0.63, 3.05)	0.85 (0.02, 1.69)
50–64	3.69 (1.60, 5.83)	−0.28 (−1.19, 0.64)
Above 65	4.22 (0.35, 8.24)	−0.72 (−2.39, 0.98)
Race/ethnicity		
White	1.09 (−0.61, 2.82)	1.12 (−0.35, 1.89)
Black	2.80 (1.05, 4.58)	0.22 (−0.56, 1.00)
Asian	4.92 (−0.46, 10.59)	2.2 (−0.20, 4.66)
Hispanic	5.35 (3.07, 7.68)	0.55 (−0.46, 1.57)
Others	2.58 (0.27, 4.94)	0.8 (−0.25, 1.85)

were obtained for the 50th percentile, as no difference in the association was observed using the 50th percentile as the only cut-off point (see Appendix B for details).

4. Discussion

We examined the associations between two daily air pollutants of $PM_{2.5}$ and O_3 exposures and ER visits related to mental disorders using 457 755 ER visits that occurred in NYC, USA, between 2010 and 2016. To our knowledge, there is only one prior study to examine the adverse effects of the short-term air pollution exposure on broadly defined mental disorders, as well as specific mental disorders, through a case-crossover design using spatially and temporally resolved $PM_{2.5}$ concentration and temperature estimates (Brokamp *et al* 2019). However, this prior study focused only on a single air pollutant ($PM_{2.5}$) and children/adolescents, whereas our results suggest that the effects of both $PM_{2.5}$ and O_3 vary by age groups. Specifically, our results indicated that the mental-disorder related ER visits increased by 2.78% (95% CI: 1.82%–3.76%) with a 10 $\mu g\,m^{-3}$ increase in ambient $PM_{2.5}$ concentration on a moving average lag 0–3 d and 0.71% (95% CI: 0.28%–1.15%)

with 10 ppb increase in ambient O_3. Furthermore, this effect was modified by age and race/ethnicity, but not by sex or surrounding greenery.

We first examined the effect of daily $PM_{2.5}$ and O_3 exposures on ER visits for any of the mental disorders examined in the present study. A significant positive association was found between ER visits for mental disorders and daily air pollutants of both $PM_{2.5}$ and O_3 exposures. The association of increased treatment services for mental disease with high levels of ambient $PM_{2.5}$ concentration is consistent with previous studies on both short-term (Gao *et al* 2017, Chen *et al* 2018, Song *et al* 2018, Lee *et al* 2019, Li *et al* 2020) and long-term (Power *et al* 2015, Kim *et al* 2016, Lin *et al* 2017, Pun *et al* 2017, Ran *et al* 2021) associations. Similarly, the positive and significant effect of O_3 on total mental disorders is generally consistent with findings from previous studies (Szyszkowicz 2007, Szyszkowicz *et al* 2016, Kioumourtzoglou *et al* 2017).

Our findings of significant effects of $PM_{2.5}$ exposure on psychotic disorders, substance abuse, and anxiety disorders agree with previous studies in China (Gao *et al* 2017, Bai *et al* 2020) and Canada (Szyszkowicz *et al* 2018). However, our results did not demonstrate significant associations between short-term exposure to $PM_{2.5}$ and ER visits related to mood disorders or dementia, while significant associations were reported in previous studies (Gao *et al* 2017, Wang *et al* 2018a, Peters *et al* 2019, Qiu *et al* 2019, Lu *et al* 2020, Shi *et al* 2020, Wei *et al* 2020). Similarly, we found significant effects of O_3 on both mood disorders and psychotic disorders but not on substance abuse, anxiety disorders, or dementia. Although several past studies have also reported positive associations between O_3 and mood disorders (Szyszkowicz 2007, Szyszkowicz *et al* 2016, Nguyen *et al* 2021), null results have also been reported (Oudin *et al.* 2018, Wang *et al.*, 2014b). One potential source of these inconsistent findings lies in differences in the source of health outcomes of previous studies, as some studies focused on hospital admissions (Qiu *et al* 2019), surveys (Shi *et al* 2020), or daily hospital visits (Wei *et al* 2020). Given that there is very limited research on the effects of air pollution exposure on specific mental disorders, further investigation is needed to corroborate our findings and to explain why air pollution was associated with exacerbations of symptoms leading to ER visits for some types of mental disorders, but not for others.

The underlying mechanisms by which air pollutants impact emergency room visits for psychiatric disorders are mostly unknown. Some previous studies reported that air pollutants may affect the mental status through their impact on inflammatory processes, the immune system, oxidative stress, and cerebral neurotransmitter concentrations (Sirivelu *et al* 2006, Van Berlo *et al* 2010, Thomson 2019).

Despite growing evidence that air pollution is significantly associated with psychiatric diseases (Szyszkowicz *et al* 2009, Gao *et al* 2017, Kim *et al* 2019), it is unclear if the processes underlying the relationship between exposure to air pollutants and mental illness reflects a shared process that cuts across mental disorders or that there are processes that are unique to particular disorders. Similarly, the associations between different air pollutants and particular mental disorders varies per study. For example, Thilakaratne *et al* (2020) found a negative association between ER visits for substance abuse and NO_2 in California, whereas the present study showed a positive association between $PM_{2.5}$ exposure and substance abuse in NYC. Increased understanding of key mechanisms will be needed to identify risk factors that contribute to susceptibility.

In the age-specific analyses, we found that associations between both air pollutants ($PM_{2.5}$ and O_3) and ER visits were more pronounced among the age group 19–34 years old relative to other age groups. For $PM_{2.5}$ only, the youth (18 years old or below) and 55–64 years were more susceptible than other age groups. In contrast, previous studies reported that older adults, particularly those aged 64 years and older, were more vulnerable in studies based in China (Li *et al* 2020) and South Korea (Cho *et al* 2014, Kim *et al* 2019). Although Thilakaratne *et al* (2020) observed that youth (below 18 years old) were vulnerable to homicide/inflicted injury related emergency department visits following exposure to high levels of carbon monoxide, this association was not significantly different from other age groups. To our best knowledge, there is only one other study (Brokamp *et al* 2019) reporting that young people were particularly vulnerable to the effects of ambient $PM_{2.5}$ exposure on risk for mental disorder outcomes.

In terms of greenspace exposure, we found no evidence that the degree of greenspace visibility surrounding individuals' residence made individuals more or less susceptible to the effects of exposure to air pollution. That is, the percent change in ER visits related to total mental disorders associated with $PM_{2.5}$ exposure was not significantly different for varying levels of greenspace exposure. However, it is possible that unique aspects of NYC may have had an impact on these results. While it seems likely that in many urban environments, greenery is positively correlated with social advantages, this is not the case in NYC. Neighborhoods in the highly affluent areas of lower and mid-town Manhattan tend to be surrounded by skyscrapers and concrete, whereas most neighborhoods in the less affluent boroughs of the Bronx and Staten Island are surrounded by thick trees at the street level. These mixed conditions in greenspace of NYC may have contributed to the elevated susceptibility to air pollution exposure in some areas, and the opposite effect in others.

The main strengths of this study are as follows: first, the use of spatially resolved daily $PM_{2.5}$ and O_3 exposure estimates enabled us to overcome the limitations of existing studies where city- or region-wide coarse air pollution estimates were used as a proxy measurement. In addition, the use of the large sample of ER visits in NYC also enabled us to investigate specific mental disorders, and assess differentiated risk for specific disease, such as substance abuse and psychotic disorders. Third, our individual-level case-crossover design automatically adjusted for time-invariant confounding and time-varying meteorological factors (ambient temperature) were controlled for in the models, providing stronger inference in potential causality than ecological study designs such as time-series and cross-sectional studies.

Our study is not short of limitations. First, spatial patterns of ER visits and their associations with socio-economic conditions have not been taken into account, and these potentially could impact individuals' reaction to $PM_{2.5}$ exposure. Second, the present study only examined $PM_{2.5}$ and O_3, and it is possible that other pollutants such nitrogen dioxide and sulfur dioxide have different associations with ER visits for mental disorders. Given the potential unique aspects of New York City, further studies in other regions are needed to confirm our findings. Perhaps of most importance, it will be critical for future studies to investigate the underlying mechanisms by which exposures to $PM_{2.5}$ and O_3 is linked to ER visits for mental disorders.
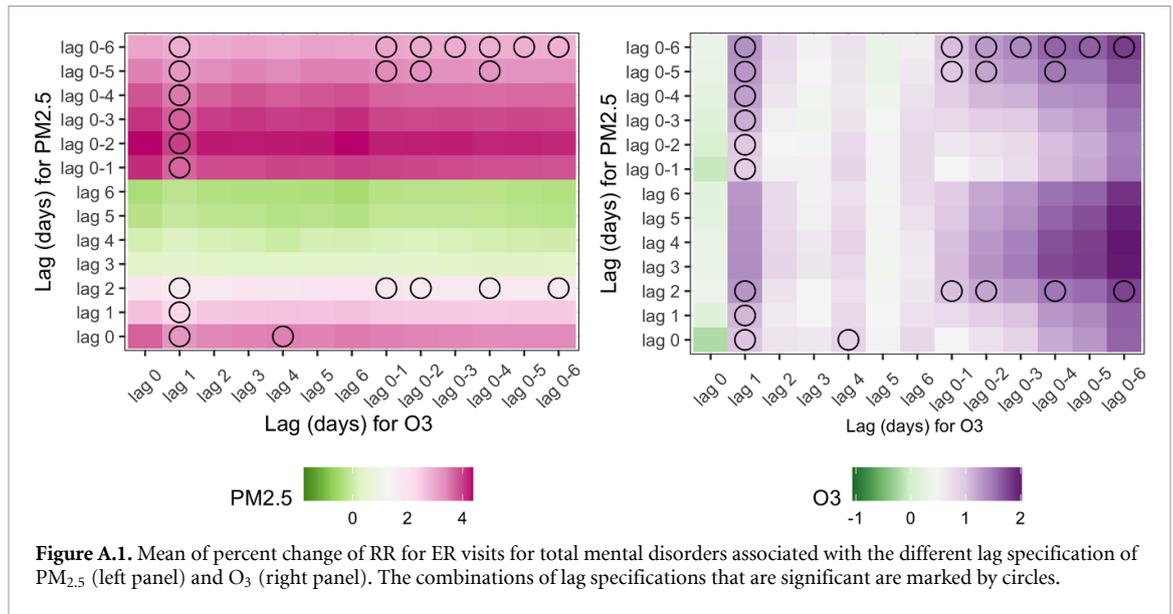
5. Conclusions

This study suggests that there is a positive association between short-term exposure to ambient fine particulate matter and increased ER visits for total mental disorders, as well as for substance abuse and psychotic disorders in particular. Our findings of higher vulnerability to air pollution among the specific age groups (i.e. 19–34 years old and youth) and non-Whites warrant follow-up research to better understand why and how these individuals are particularly susceptible.

Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but data are available from the corresponding author on reasonable request.

Appendix A. Identification of main lag

We investigated delayed effects beyond lag 0 to lag 6 by calculating the percent changes in the risk of visiting ER for total mental disorders over different days for both single day and accumulated day (moving average) lag. To account for the delayed effects of the two

Figure A.1. Mean of percent change of RR for ER visits for total mental disorders associated with the different lag specification of PM$_{2.5}$ (left panel) and O$_3$ (right panel). The combinations of lag specifications that are significant are marked by circles.

air pollutants simultaneously, we considered 13 different lags {lag 0, lag 1, . . . , lag 6, lag 0–1, lag 0–2, . . . , lag 0–6} for each pollutant, which resulted in a total of 169 different combinations of lag specifications for PM$_{2.5}$ and O$_3$.

The results are summarized in figure A.1 where the shade represents the mean of percent changes of RRs for different combinations of lag specification for PM$_{2.5}$ (left panel) and O$_3$ (right panel) overlapped with circles to denote the lag specifications where both PM$_{2.5}$ and O$_3$ were statistically significant. The results suggest that all the accumulated day (moving average) lags yielded high RR for PM$_{2.5}$ (left panel), but the maximum percent change of RR was associated with the single day lag (lag 1) and moving average lag 0-6 for O$_3$ (right panel). When both PM$_{2.5}$ and O$_3$ were taken into account simultaneously, however, we found only a subset (23 combinations) of lag specifications out of 169 combinations (13 × 13) were significant, and the moving average lag 0–3 d for PM$_{2.5}$ and single day lag (lag 1) for O$_3$ yielded the highest RR value (2.78, 95% CI (1.82, 3.75) for PM$_{2.5}$; 0.72, 95 % CI (0.29, 1.15) for O$_3$). Thus we selected moving average lag 0–3 and single day lag (lag 1) as the main lag for PM$_{2.5}$ and O$_3$, respectively, throughout the analysis.

Appendix B. Effect modification by greenspace exposure

We examined the sensitivity of the risk of visiting ER related to mental disorders associated with the exposure to ambient PM$_{2.5}$ and O$_3$ by varying levels of greenspace surrounding individuals' residence. Specifically, we estimated the percent change in RR of ER visits related to total mental disorders from exposure to ambient PM$_{2.5}$ and O$_3$ by quartile of GVI

Table B.1. Percent change in ER visits for total mental disorders by greenspace exposure at the extended lag period (lag 0–3).

GVI Quartiles	PM$_{2.5}$	O$_3$
Quartile 1 (0.00–6.08)	3.04 (1.13, 4.98)	1.05 (0.19, 1.93)
Quartile 2 (6.08–14.05)	2.99 (1.06, 4.95)	0.27 (−0.58, 1.14)
Quartile 3 (14.05–26.76)	2.06 (0.15, 4.01)	1.37 (0.51, 2.24)
Quartile 4 (26.76–92.45)	3.08 (1.14, 5.06)	0.15 (−0.7, 1.01)

measured at one's residence. The results summarized in Table B.1 suggested that the changes in risk are similar to each other in the range of 2.06 and 3.08 for PM$_{2.5}$ and 0.15 and 1.37 for O$_3$ regardless of the levels of surrounding greeneries. No statistically significant differences were found between any pair of levels of greenness.

We also conducted a stratified analysis based on 50th percentile of GVI values, and we found that the percent change (2.56, 95% CI (1.2, 3.94)) in risk at high (>50th percentile) levels of greenness is not significantly different from that (3.01, 95% CI (1.6, 4.38)) at the low (⩽50th percentile) level of greenness for PM$_{2.5}$. Similarly, no significant difference was found between the percent change (0.76, 95% CI (0.15, 1.37)) in risk at high levels of greenness and that (0.66, 95% CI (0.05, 1.27)) at the lower level of greenness for O$_3$, respectively.

Appendix C. Model specification

The model formulation for the conditional logistic model with a two-pollutant model of PM$_{2.5}$ and O$_3$ can be written as:

$$Y_{i,j} \approx Bernoulli(\pi_{i,j})$$

$$\pi_{i,j} = \frac{\exp\{\alpha + \beta_1 PM_{s_i,j} + \beta_2 O_{s_i,j} + ns(Temp_{s_i,j}, df_1) + ns(Dew_{s_i,j}, df_2)\}}{\sum_{j' \in k(j)} \exp\{\alpha + \beta_1 PM_{s_i,j'} + \beta_2 O_{s_i,j'} + ns(Temp_{s_i,j'}, df_1) + ns(Dew_{s_i,j'}, df_2)\}},$$

$Y_{i,j}$ indicates whether the event that the ith individual' ER visit for mental disorder occurs in time interval j in the pre-specified reference window $k(j)$ ($Y_{i,j} = 1$, event; 0, not). The set of reference periods is denoted as $k(j) = \{j - 14, j - 7, j, j + 7, j + 14\}$. The spatially and temporally resolved exposures at the location s_i (i.e. the residence of ith individual) and time j (day) for air pollution (PM$_{2.5}$ and O$_3$) and temperature, and dew point temperature are denoted as $PM_{s_i,j}, O_{s_i,j}, Temp_{s_i,i}, Dew_{s_i,j}$, respectively. The smoothing function is denoted as ns with the corresponding degree of freedom df_1, df_2 for temperature and dew point temperature, respectively. To estimate relative risk (RR), we reestimated the model coefficients ($\hat{\beta}_1, \hat{\beta}_2$) with the different sets of data $Y_{i,j}$.

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