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A stronger association of mental disorders with smaller particulate matter and a modifying effect of air temperature☆

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A R T I C L E I N F O

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A B S T R A C T

Mental disorders (MDs) can be triggered by adverse weather conditions and particulate matter (PM) such as $PM_{2.5}$ and PM_{10} (aerodynamic diameter $\leq$2.5 μm and $\leq$10 μm). However, there is a dearth of evidence on the role of smaller PM (e.g. PM_1, aerodynamic diameter $\leq$1 μm) and the potential modifying effects of weather conditions. We aimed to collect daily data on emergency department visits and hospitalisations for schizophrenia-, mood-, and stress-related disorders in a densely populated Chinese city (Hefei) between 2016 and 2019. A time-stratified case-crossover analysis was used to examine the short-term association of MDs with PM_1, $PM_{2.5}$, and PM_{10}. The potential modifying effects of air temperature conditions (cold and warm days) were also explored. The three size-fractioned PMs were all associated with an increased risk of MDs; however, the association differed between emergency department visit and hospitalisation. Specifically, PM_1 was primarily associated with an increased risk of emergency department visit, whereas $PM_{2.5}$ was primarily associated with an increased risk of hospitalisation, and PM_{10} was associated with an increased risk of both emergency department visit and hospitalisation. The PM-MD association appeared to be greatest (although not significant) for PM_1 (odds ratio range: 1.014–1.055), followed by $PM_{2.5}$ (odds ratio range: 1.001–1.009) and PM_{10} (odds ratio range: 1.001–1.006). Furthermore, the PM-MD association was observed on cold days; notably, the association between PM and schizophrenia-related disorders was significant on both cold and warm days. Our results suggest that the smaller the PM, the greater the risk of MDs, and that the PM-MD association could be determined by air temperature conditions.

1. Introduction

A growing number of epidemiological studies worldwide have reported that ambient particulate matter (PM) poses a serious threat to public health, contributing to morbidity and mortality from a broad disease spectrum, including the widely reported cardiovascular and respiratory diseases (Janssen et al., 2013; Wu et al., 2022). PM exposure is closely associated with the development of central nervous system inflammation, which may trigger changes in psychiatric pathology and physiology (Wang et al., 2017) and play a crucial role in the onset or exacerbation of mental disorders (MDs) such as schizophrenia, depression, and bipolar disorder (Qiu et al., 2022; Song et al., 2022). Considering a rapid increase in disability-adjusted life-years attributable to MDs from 3.1 to 4.9% globally from 2010 to 2019 (Collaborators, 2022), the impact of PM on MDs is increasingly in need of widespread attention.

Studies have reported an association of MDs with PM such as $PM_{2.5}$

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(aerodynamic diameter ≤2.5 μm) and PM_{10} (aerodynamic diameter ≤10 μm) (C Chen et al., 2018a; Qiu et al., 2019; Song et al., 2022), with mixed findings regarding which kind of PMs could pose a greater risk. For example, a study conducted in Chengdu, China, found that, for each 10 μg/m^3 increase in $PM_{2.5}$ and PM_{10}, the risk of hospitalisations for MDs increased by 2.89% and 1.91%, respectively (Qiu et al., 2019). In contrast, another study conducted in Shanghai, China, did not find a significant association between $PM_{2.5}$ and hospitalisations for MDs, but noted a significant association with PM_{10} (C Chen et al., 2018a). This discrepancy may be partly due to the distinct study designs, study populations, and types and concentrations of toxic substances carried by PM across regions (Li et al., 2019). Therefore, it is necessary to further determine and compare the risk of MD after exposure to $PM_{2.5}$ and PM_{10} in affected areas (Gao et al., 2021; Q Wei et al., 2022). In addition, another smaller PM such as PM_1 (aerodynamic diameter ≤1 μm) is also gaining research attention, with a greater risk for cardiovascular and respiratory diseases after exposure to PM_1 compared to $PM_{2.5}$ and PM_{10} (Wang et al., 2021; Yin et al., 2020). Given that different size-fractioned PMs (e.g., PM_1, $PM_{2.5}$, and PM_{10}) vary in their sources, surface-to-volume ratios, and potential to enter the body (Heyder, 2004; Khan et al., 2021; Kodros et al., 2018; Wang et al., 2008), MDs may respond differently after exposure to distinct PMs. However, the short-term association between PM_1 and MDs has not been reported, and it remains unclear whether the effect of PM_1 is similar to or greater than $PM_{2.5}$ and PM_{10}.

Additionally, weather conditions are a potential factor that may influence the health effects of PM. PM concentrations appear to be higher in cold weather conditions and may exhibit more severe cytotoxicity and oxidative damage (Yang et al., 2022), leading to a higher health risk. For example, a study in New York revealed that the cardiovascular disease risk associated with $PM_{2.5}$ was higher under cooler air temperature conditions (Hsu et al., 2017). Although studies have reported differences in the association between PM and MDs during the cold and warm seasons (Oudin et al., 2018; Song et al., 2018), the possible moderating effects of air temperature conditions on the PM-MD association have not yet been explored. We, therefore, conducted a time-stratified case-crossover study to examine the association between three size-fractioned PMs and MD in an eastern city of China, aiming to assess and compare the risk of MD after exposure to PM_1, $PM_{2.5}$, and PM_{10} and explore the potential modifying effects of distinct air temperature conditions (cold and warm days).

2. Methods

2.1. Data collection on MDs

This study was conducted in Hefei, China (Fig. S1). To reflect the association between PM and different stages of MD, we obtained daily records of emergency department visit (EDV) and hospitalisation between January 1, 2016 and December 31, 2019 from the Anhui Provincial Mental Health Center, a government-authorised specialized hospital located in Hefei that provides medical services for patients with mental illnesses, especially schizophrenia.

For each patient, we extracted information on the date of visiting the emergency department or hospitalisation and the cause of disease based on the International Classification of Diseases, 10th Revision (ICD-10). We included patients who were local residents and those with one of the three cause-specific ICD-10 codes associated with MD, including schizophrenia-related disorders (F20–F29), mood-related disorders (F30–F39), and stress-related disorders (F40–F48), as these are the major contributors to the mental disease burden and have been previously reported to be affected by PM (Braithwaite et al., 2019; Collaborators, 2022; Qiu et al., 2022). We excluded cases that were not from the urban areas of Hefei and those that did not have the MD-related ICD-10 code or the ICD-10 code was missing.

2.2. Data collection on environmental variables

Daily mass concentrations (hereafter referred to as concentrations) of PM_1, $PM_{2.5}$, and PM_{10} were obtained from the online dataset platform of the China High Air Pollutants (CHAP) (https://weijing-rs.github.io/product.html), which has been widely used in previous research on the association between air pollution and health outcomes (Cai et al., 2022; Liu et al., 2022). This dataset covers the Chinese mainland, with a temporal resolution of every day and a spatial resolution of 1 km × 1 km grids (Wei et al., 2019; Wei et al. 2020; Wei et al. 2021a, b). We extracted daily PM concentrations for all grids within the urban area of Hefei. In addition, daily concentrations of gaseous pollutants, including sulphur dioxide (SO_2), carbon monoxide (CO), ozone (O_3), and nitrogen dioxide (NO_2) in the same study area were also extracted for sensitivity analysis (He et al., 2022; J Wei et al., 2022a, b; Wei et al., 2023). In line with previous studies (Myung et al., 2019; Tian et al., 2017), we calculated the daily mean concentrations of air pollutants within the urban area of Hefei and then estimated the air pollutant concentrations for each patient based on the date of EDV or hospitalisation.

In addition, daily meteorological variables, including daily mean temperature and relative humidity for the same period were obtained from the National Centers for Environmental Information (https://www.ncdc.noaa.gov), which comprises meteorological data from more than 400 monitoring stations in China. We included meteorological records from the ground-based monitoring station closest to the study area in the final analysis (Fig. S1) as did in previous literature (Chen et al., 2019; Zhang et al., 2019).

2.3. Statistical analysis

A time-stratified case-crossover design was used to investigate the short-term association between size-fractioned PMs and MDs. This design allows environmental exposures to be assessed through a "case matching its controls"; specifically, exposures on the day of or the day prior to the case event period are compared with exposures on other control periods of the same month, week, and day of the year; so, time-varying confounders such as day of the week, seasonality and temporal trends as well as individual characteristics (e.g., gender, age, occupation) that barely change within a short period can be controlled automatically (Janes et al., 2005; Maclure, 1991).

A conditional logistic regression model was applied to fit the exposure-response relationship between short-term exposure to PM and MD. Previous studies have suggested a PM-MD association on the day of exposure or a few days later (Qiu et al., 2022; Song et al., 2018; Wang et al., 2018); therefore, we used a maximum lag of 7 days (day of exposure [lag 0 d] to day 6 of exposure [lag 6 d]) in the final analysis. Considering the possible influence of public holidays and meteorological factors on MDs (C Chen et al., 2018a; Qiu et al., 2022), we added dichotomous variables ("0", non-holiday; "1", holiday) to the model to adjust for public holiday effects, and used a natural cubic spline with 3 degrees of freedom (*df*) to control for the effect of daily mean temperature based on the Akaike Information Criterion (Table S1) (Szyszkowicz et al., 2020). In our preliminary exploration, we observed a significantly increased risk of MD after exposure to high concentrations of each PM, and the exposure-response relationship was approximately linear under high-concentration conditions (Fig. S2–S13). Therefore, we focused on high concentrations of PM (≥90th percentile) in the subsequent analysis (Bai et al., 2020). At the same time, the association between each PM and MD was reported as an odds ratio (OR) and 95% confidence interval (CI) associated with each 1 μg/m^3 increment. The 90th percentile of PM concentrations is shown in Table S2. Differences in the association between each PM and the MD were tested using the *Z*-test (Altman and Bland, 2003).

To further investigate the short-term association between MD and PM through modifications in air temperatures, we divided the study period into cold and warm days using a cut-off of 19.4 °C (R Chen et al., 2018b; Fu et al., 2018), chosen because of our previously reported minimum morbidity temperature in the non-linear (U-shaped) association between air temperature and schizophrenia in Hefei (Tang et al., 2021). We then separately examined the association between high PM concentrations and MD on cold and warm days (Table S2). Similarly, PM-related mental health risk was reported as an OR associated with each 1 μg/m^3 increase across air temperature conditions, and a *Z*-test was employed to test the subgroup difference (Altman and Bland, 2003).

2.4. Sensitivity analysis

Two sensitivity analyses were conducted to check the robustness of our findings: additional adjustments for relative humidity in the model and the use of a two-pollutant model instead of a single-pollutant model. All analyses were conducted in R software (version: 4.2.2) using the packages "survival" and "dlnm". A two-sided *P*-value <0.05 was considered statistically significant.

3. Results

3.1. Statistical description

We included 5331 cases of EDVs for MD and 6274 cases of hospitalisations for MDs, with more cases occurring on cold days. Among cause-specific MDs, schizophrenia-related disorders (F20–F29) were most commonly reported (EDV: 57.70%; hospitalisation: 51.56%), followed by mood-related disorders (F30–F39) (EDV: 27.12%; hospitalisation: 36.90%) and stress-related disorders (F40–F48) (EDV: 15.18%, hospitalisation: 11.54%) (Table 1). During the study period, daily mean concentrations of PM_1, $PM_{2.5}$, PM_{10}, NO_2, SO_2, O_3, and CO as well as the mean temperature and relative humidity were 17.7 μg/m^3, 49.4 μg/m^3, 79.7 μg/m^3, 39.9 μg/m^3, 102.9 μg/m^3, 11.1 μg/m^3, 0.9 mg/m^3, 16.9 °C and 73.2%, respectively (Table 2). Except for O_3, the concentrations of the air pollutants were significantly higher on cold days than on warm days (Table 2). The differences in exposure between the case and control periods were not significant, except for exposure to PM_{10}, NO_2, and relative humidity in hospitalised cases (Table S3).

3.2. Short-term associations of MDs with PM_1, $PM_{2.5}$, and PM_{10}

Table S4 shows an increased risk of MDs associated with each 1 μg/m^3 increase in PM, but this association varied by EDV and hospitalisation. Specifically, when the PM_1 concentration increased, a significant increase in the risk of schizophrenia-, mood-, and stress-related disorders was observed only in the EDV group. In contrast, when $PM_{2.5}$ concentration increased, a significant increase in the risk of total and cause-specific MDs was observed only during hospitalisation. Unlike PM_1 and $PM_{2.5}$, an increased risk of EDVs and hospitalisations for total and cause-specific MDs was associated with an increase in PM_{10} concentrations.

Table 1
Descriptive statistics of mental disorders during whole study period and on cold and warm days in Hefei, China, 2016–2019.

Period	Total (F20–F48)	Schizophrenia-related (F20–F29)	Mood-related (F30–F39)	Stress-related (F40–F48)
Emergency department visit				
Whole study period [**N (%)**]	5331 (100)	3076 (57.70)	1446 (27.12)	809 (15.18)
Cold days [**N (%)**]	3018 (100)	1748 (57.92)	825 (27.34)	445 (14.74)
Warm days [**N (%)**]	2313 (100)	1328 (57.41)	621 (26.85)	364 (15.74)
Hospitalisation				
Whole study period [**N (%)**]	6274 (100)	3235 (51.56)	2315 (36.90)	724 (11.54)
Cold days [**N (%)**]	3310 (100)	1716 (51.84)	1087 (32.84)	366 (11.06)
Warm days [**N (%)**]	2964 (100)	1519 (51.25)	948 (31.98)	358 (12.08)

Table 2
Description of air pollutants and meteorological variables during whole study period and on cold and warm days in Hefei, China, 2016–2019.

Variables	Whole study period [mean (SD)]	Cold days [mean (SD)]	Warm days [mean (SD)]	*P*-value
PM_1 (μg/m^3)	17.7(14.5)	24.4(15.5)	11.1(9.7)	<0.001
$PM_{2.5}$ (μg/m^3)	49.4(28.1)	61.1(31.0)	35.1(14.5)	<0.001
PM_{10} (μg/m^3)	79.7(37.6)	92.0(39.6)	64.7(28.4)	<0.001
SO_2 (μg/m^3)	11.1(5.1)	12.3(5.8)	9.5(3.6)	<0.001
NO_2 (μg/m^3)	39.9(16.3)	46.6(17.3)	31.7(10.2)	<0.001
O_3 (μg/m^3)	102.9(44.29)	78.4(30.8)	132.9(39.6)	<0.001
CO (μg/m^3)	0.9(0.3)	0.9(0.3)	0.8(0.1)	<0.001
Mean temperature (°C)	16.9(9.4)	9.7(5.8)	25.6(3.7)	<0.001
Relative humidity (%)	73.2(15.0)	72.2(16.3)	74.3(13.0)	0.009

SD, standard deviation; The *P*-value was based on the *t*-test.

Fig. 1 shows a comparison of the associations between MD and PM_1, $PM_{2.5}$, and PM_{10} exposures. The results showed a significantly greater association of EDVs for schizophrenia-related disorders with PM_1 than with $PM_{2.5}$ and PM_{10} ($P < 0.05$, based on the *Z*-test); the ORs were 1.037 (95% CI: 1.009–1.066, lag 2), 1.004 (95% CI: 0.999–1.008, lag 0), and 1.003 (95% CI: 1.000–1.006, lag 0), respectively. In terms of hospitalisations for total MDs and schizophrenia-related disorders, the association was significantly stronger for $PM_{2.5}$ (1.007 [95%CI: 1.004–1.010, lag 2] and 1.009 [95%CI: 1.006–1.013, lag 2], respectively) than for PM_{10} (1.003 [95%CI: 1.002–1.005, lag 2] and 1.004 [95%CI: 1.002–1.007, lag 2], respectively) ($P < 0.05$, based on the *Z*-test). Among other cause-specific MDs, only the estimated OR was higher after exposure to PM_1 than that exposure to $PM_{2.5}$ and PM_{10} ($P > 0.05$, based on the *Z*-test).

3.3. Modification by air temperature

Table S5 provides OR estimates for the association between each 1 μg/m^3 increase in PM and EDVs for MDs on cold and warm days. The results showed that PM_1 was significantly and positively associated with schizophrenia-related disorders on both cold (1.059 [95% CI: 1.015–1.105, lag 2]) and warm days (1.056 [95% CI: 1.005–1.111, lag 2]); whereas, on cold days, PM_1 was significantly and positively associated with mood- (1.069 [95% CI: 1.006–1.136, lag 4]) and stress-related disorders (1.098 [95% CI: 1.015–1.187, lag 3]). PM_{10} was only marginally associated with total MDs (1.004 [95% CI: 1.000–1.007, lag 0]) and stress-related disorders (1.008 [95% CI: 1.000–1.015, lag 0]) on warm days. There was no significant positive association between $PM_{2.5}$ and MD on either cold or warm days.

Table S6 provides the OR estimates for the association between each 1 μg/m^3 increase in PM and hospitalisations for MDs on cold and warm days. PM_1 was significantly and positively associated with the risk of schizophrenia-related disorders (1.056 [95% CI: 1.004–1.111, lag 2]) only on cold days. Similarly, $PM_{2.5}$ and PM_{10} were significantly associated with total and cause-specific MDs only on cold days, with the exception of schizophrenia-related disorders, which had a significant increase in risk after exposure to $PM_{2.5}$ on both cold (1.013 [95% CI: 1.008–1.019, lag 2]) and warm days (1.018 [95% CI: 1.002–1.034, lag 1]).

By comparing the PM-MD association on cold and warm days

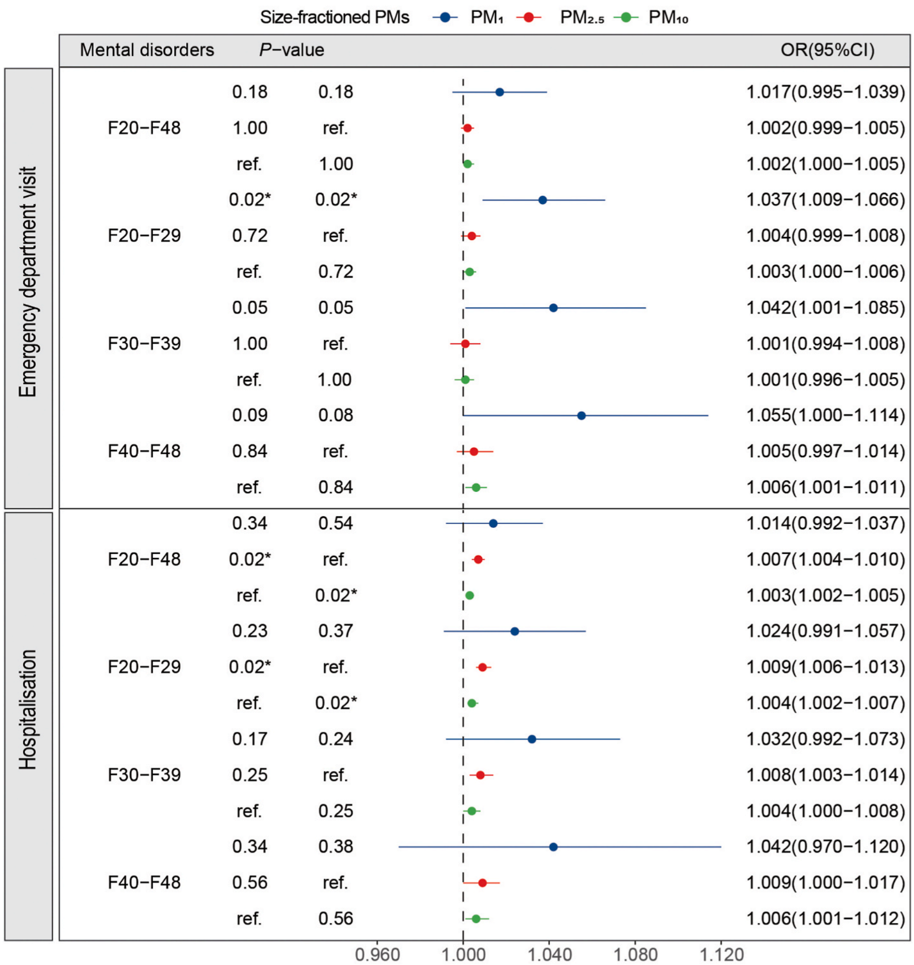

Fig. 1. Comparisons of the association of mental disorders with size-fractioned particulate matters. Risk estimates are reported as odds ratios associated with each 1 μg/m^3 increase in PM_1, $PM_{2.5}$, and PM_{10} above the 90th percentile of mass concentration distribution. The *P*-value was based on the *Z*-test.

(Fig. 2), only the association between PM_{10} and hospitalisations for total MDs differed between cold and warm days, with a significantly higher OR on cold days than that on warm days ($P < 0.05$, based on the *Z*-test).

3.4. Sensitivity analyses

Table S7 shows the estimated OR for MDs associated with PM after controlling for relative humidity in the main model. Tables S8–S10 show the estimated OR of MDs after exposure to PM_1, $PM_{2.5}$, and PM_{10}, using a two-pollutant model instead of a single-pollutant model. The results of these sensitivity analyses were generally similar to those of the main model (Table S4), suggesting that our findings are robust.

4. Discussion

Ambient PM pollution is a well-recognised global health hazard, with growing evidence supporting the greater health effects of smaller PM (Wang et al., 2021; Yin et al., 2020). However, existing studies have primarily examined the mental health effects of $PM_{2.5}$ and PM_{10} (Lu et al., 2020; Qiu et al., 2022), leaving it unknown whether patients with MDs are at higher risk after exposure to a smaller PM such as PM_1. To this end, we investigated the short-term association of EDVs and hospitalisations for MDs with different PMs (PM_1, $PM_{2.5}$, and PM_{10}) and further explored the modifying effect of air temperature. The following three interesting findings were obtained: all size-fractioned PMs were associated with an increased risk of total and cause-specific MDs; PM_1 had the strongest association with MDs, especially schizophrenia-related disorders, followed by $PM_{2.5}$ and PM_{10}; and the positive association between MDs and PMs was mainly noted on cold days, whereas the risk of schizophrenia-related disorders was also significantly increased after exposure to PM_1 and $PM_{2.5}$ on warm days.

Our findings demonstrated that both $PM_{2.5}$ and PM_{10} were associated with an increased risk of total and cause-specific MDs, which is consistent with previous studies (Muhsin et al., 2022; Song et al., 2018; Song et al., 2022). For example, studies reporting that each 10 μg/m^3 increase in $PM_{2.5}$ and PM_{10} is associated with a 0.48% and 0.32% increase in the risk of mental and behavioural disorders, and 0.50% and 0.47% increase in the risk of schizophrenia, respectively (Song et al., 2018; Song et al., 2022). However, most studies have focused on a single status of MD, such as EDV (Muhsin et al., 2022) or hospitalisation (Song et al., 2018), which makes it difficult to determine the status of mental diseases most or least affected by PM. EDV often reflects an acute episode of illness, whereas hospitalisation is related to severe deterioration of illness. To better capture the association between PM and MD, we looked at both EDV and hospitalisation and observed some differences, such as a stronger PM_1-EDV association than PM_1-hospitalisation association, and a stronger $PM_{2.5}$-hospitalisation association than $PM_{2.5}$-EDV association. This suggests that future research should be aware of the distinction between EDV and hospitalisation, and make rational use of case data to gain a more comprehensive understanding of the association between PMs and MDs, thereby guiding the allocation of medical resources.

In addition to $PM_{2.5}$ and PM_{10}, we investigated the association between PM_1 and MDs. To the best of our knowledge, no study has investigated short-term association thereof, which limits the direct

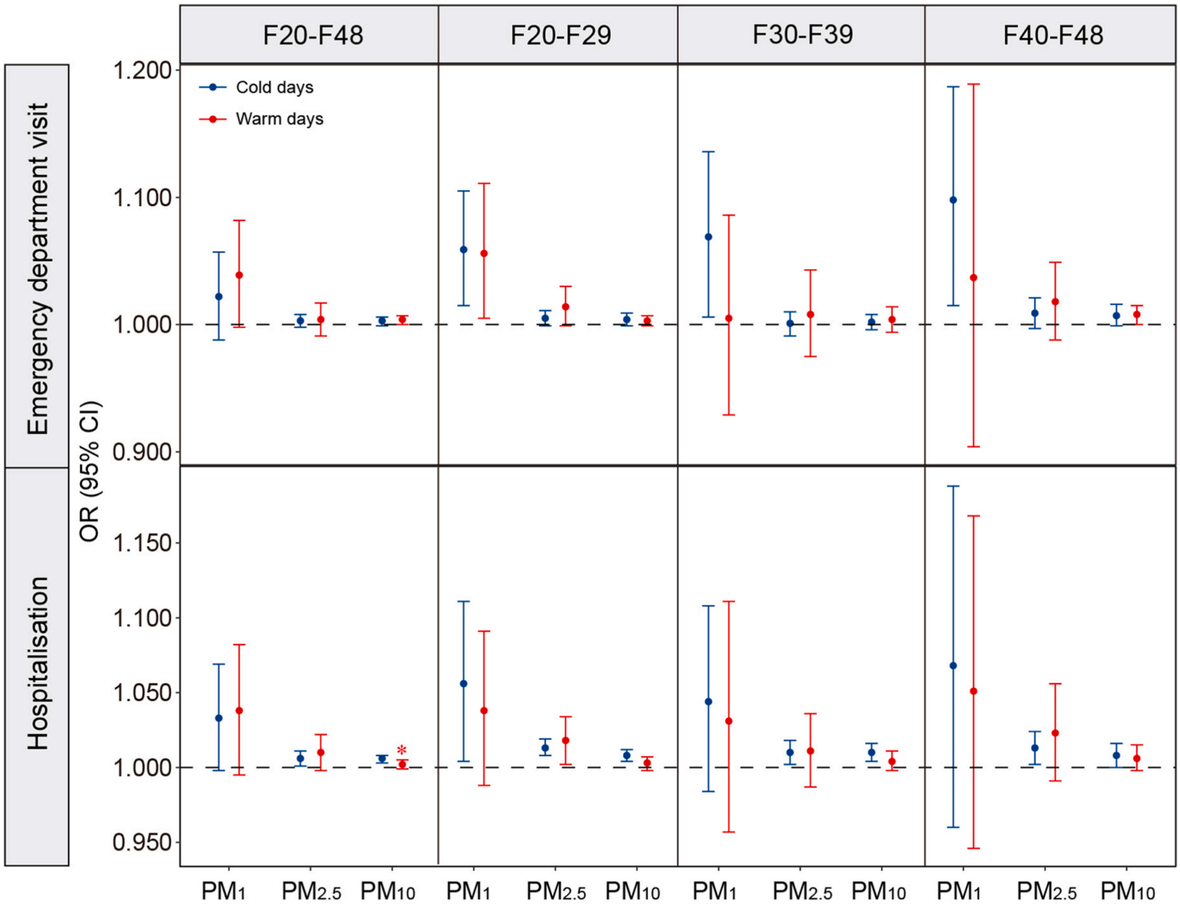

Fig. 2. Comparisons of the association of mental disorders with particulate matter between cold and warm days. Risk estimates were reported as odds ratios associated with each 1 μg/m^3 increase in PM_1, $PM_{2.5}$, and PM_{10} above the 90th percentile of mass concentration distribution; **P*-value for difference <0.05, based on the *Z*-test.

comparison of our results with prior studies. Smaller PM poses a greater threat to human health (Wang et al., 2021; Yin et al., 2020). For example, each 10 μg/m^3 increase in PM_1 is associated with a 0.29% increase in the risk of cardiovascular mortality, which is significantly higher than $PM_{2.5}$ and PM_{10} (Yin et al., 2020). Likewise, our study provides new evidence that a smaller PM may pose a greater risk of MD. Therefore, focusing on PM with a smaller particle size (e.g. PM_1) rather than $PM_{2.5}$ and PM_{10} is also of great significance in reducing the disease burden of MDs and guiding the implementation of measures to prevent and control MDs.

Population- and animal-based studies have suggested that various toxic substances carried by PM can cross the blood-brain barrier and enter the central nervous system. These toxicants can contribute to neurotoxicity by inducing oxidative stress, neuroinflammation, endoplasmic reticulum stress, mitochondrial dysfunction, and dysregulation of protein homeostasis, which, to a certain extent, leads to structural damage to the brain as well as alteration of cognitive functions, further accelerating the deterioration of patients with MDs (Iqubal et al., 2020; Liu et al., 2017; Wang et al., 2017). However, differences in the sources, surface-to-volume ratios, and potential for entry into the body may lead to differences in the toxicity of different PM (Heyder, 2004; Khan et al., 2021; Kodros et al., 2018; Wang et al., 2008). Anthropogenic sources (e.g. combustion and secondary particle formation) contribute significantly to PM_1 (Khan et al., 2021), and vehicle and combustion emissions are probably the main sources of the most toxic substances (e.g. PAHs), suggesting that PM_1 may concentrate the main toxic substances (Mesquita et al., 2014). In addition, the size of PM determines the adsorption area of toxic substances on its surface and the depth of deposition in the body (Heyder, 2004). For example, PM_{10} is deposited more in the upper respiratory tract, while $PM_{2.5}$ reaches deeper into the lung parenchyma in the lower respiratory tract (Kodros et al., 2018). Nevertheless, PM_1 is more likely to enter the alveoli and release more toxic substances into the circulatory system (Heyder, 2004), with the possibility of crossing the blood-brain barrier to induce neuroinflammation, oxidative stress, and neurological damage (Iqubal et al., 2020; Liu et al., 2017; Wang et al., 2017). However, as PM is a complex mixture of multiple substances, it is difficult to provide a plausible explanation for the differential health effects of size-fractioned PMs on MDs, and the potential mechanisms thereof need to be further explored.

Our study further examined the role of different air temperature conditions in modifying the mental health effects of PM and found a positive association between PM and MD, mainly on cold days, which is consistent with previous studies that PM seems to be more strongly associated with mental and behavioral disorders during the cold season (Lu et al., 2020; Song et al., 2018). There are several explanations for these results. Previous studies on the association between air temperature and mental health have demonstrated a higher risk of MD on cold days (Bundo et al., 2021; Zhang et al., 2020). In addition, PM concentrations are typically higher on cold days than on warm days (Table 2) and are likely to carry more toxic substances on these days (Yang et al., 2022). Therefore, low temperatures and PM on cold days may jointly affect mental health and pose additional risks. In contrast, on warm days, high outdoor temperatures, especially extremely high temperatures, may motivate people to spend more time indoors, thereby reducing exposure to outdoor temperatures and PM and contributing to a lower risk of MD. Notably, schizophrenia-related disorders seem to be at high risk after exposure to PM on both cold and warm days, suggesting that even if PM concentrations are lower on warm days, medical aid providers should pay attention to patients with schizophrenia. However, the physiological response of the body to the combined effects of air temperature and PM is complex and warrants further research.

This study has a few limitations. First, we focused on the short-term association between PM and MDs in only one city, and caution is needed regarding regional extrapolation of our results. Second, as with previous studies (Myung et al., 2019; Tian et al., 2017), the assessment of PM exposure at the individual level could not be owing to the incompleteness of address information for each patient; therefore, PM exposure measurement bias cannot be eliminated. Third, we utilised a case-crossover design, which limited the inference of a causal association between PM and MDs. Fourth, the 95%CI of OR estimates was wide in this study, which may be due to a variety of factors, such as the small sample size and other confounders that were not considered here. Therefore, more research with larger sample sizes and better methods is needed to explore the PM-MD association. Finally, this study only focused on the pre-pandemic period of corona virus disease 2019. However, the impact of this pandemic cannot be ignored as there were significant changes in PM concentrations and the MD morbidity before and after the pandemic (Collaborators, 2021; Liu et al., 2021).

5. Conclusion

We provided novel evidence that high concentrations of three size-fractioned PMs (PM_1, $PM_{2.5}$, and PM_{10}) are all associated with an elevated risk of EDVs and hospitalisations for total and cause-specific MDs, with PM_1 appearing to have the greatest risk estimates, followed by $PM_{2.5}$ and PM_{10}. Notably, the PM-MD association may vary according to the type of medical assistance used. Specifically, PM_1 is primarily associated with EDV, while $PM_{2.5}$ is primarily associated with hospitalisation; importantly, PM_{10} is associated with both EDV and hospitalisation. In addition, the PM-MD association was observed primarily on cold days, with the exception of schizophrenia-related disorders, which were at high risk on both cold and warm days. Nevertheless, more in-depth studies are warranted to validate our results and to better guide the prevention of mental health hazards from PM pollution.

Competing financial interests

The authors declare they have no actual or potential competing financial interests.

CRediT authorship contribution statement

Keyu Wu: Writing – original draft, Software, Methodology, Formal analysis. **Junwen Tao:** Visualization, Methodology, Formal analysis. **Qiyue Wu:** Visualization, Methodology, Formal analysis. **Hong Su:** Writing – review & editing. **Cunrui Huang:** Writing – review & editing. **Qingrong Xia:** Data curation. **Cuizhen Zhu:** Data curation. **Jing Wei:** Data curation. **Min Yang:** Methodology, Formal analysis. **Junwei Yan:** Data curation. **Jian Cheng:** Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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Appendix ASupplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2024.123677

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