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RESEARCH

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The impact of particulate matter exposure on global and domain-specific cognitive function: evidence from the Chinese Square Dancer Study

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Abstract

Background There is growing evidence that exposure to particulate matter (PM) is associated with impaired cognitive function. However, limited studies have specifically examined the relationship between PM exposure and domain-specific cognitive function.

Methods This study involved 2,668 female participants from the *Lifestyle and Healthy Aging of Chinese Square Dancer Study*. Global cognitive function was assessed using a composite Z-score derived from four tests: the Auditory Verbal Learning Test (AVLT), Verbal Fluency Test (VFT), Digit Symbol Substitution Test (DSST), and Trail Making Test-B (TMT-B). These tests evaluated specific cognitive subdomains: memory (AVLT), language (VFT), attention (DSST), and executive function (TMT-B). PM concentrations were estimated using a Random Forest (RF) model, which calculated the average concentrations over 1-year and 3-year periods at a high grid resolution of 1×1 km. Mixed linear regression was employed to explore the association between PM exposure and cognitive function.

Results After adjusting for basic socio-demographic factors, a 10 mg/m^3 increase in 3-year exposure to PM_{10} was significantly associated with a decrease in the DSST score by -0.05 (95% confidence interval [CI]: -0.11, 0) and an increase in the TMT-B score by 0.05 (95% CI: 0.01, 0.1). When further adjusting for gaseous pollutants (SO_2, NO_2, and O_3), even stronger associations were observed between 3-year exposure to either $PM_{2.5}$ or PM_{10} and performance in both global cognition and specific cognitive subdomains. Specifically, in the DSST subdomain, a 10 μg/m^3 increase in 1-year PM_{10} exposure was associated with a decrease in the score by -0.10 (95% CI: -0.15, -0.04). Age-stratified analyses further indicated that older participants were consistently more vulnerable to PM exposure. Notably, 3-year exposure to both $PM_{2.5}$ and PM_{10} was linked to declines in DSST scores across both middle-aged and older age groups.

Conclusion Ambient PM exposure was significantly associated with performance in global cognitive function and specific cognitive domains among Chinese females. Female populations over 65 years old were more susceptible to the adverse effects of $PM_{2.5}$ and PM_{10}. Among the four subdomains, the DSST showed the strongest association with

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PM exposure, even at earlier ages, suggesting that impaired attention may serve as an early warning sign of cognitive decline.

Clinical trial number Not applicable.

Keywords Particulate matters, Domain-specific cognitive function, Attention

Introduction

With the rapid growth of the aging population, age-related cognitive decline and dementia have garnered increasing attention. It is estimated that approximately 9.83 million people in China are affected by Alzheimer's disease, while 3.92 million suffer from vascular dementia [1, 2]. Dementia, a neurodegenerative disorder once considered irreversible, presents significant treatment challenges. However, compared to treating dementia, preventing Alzheimer's disease by addressing cognitive decline at its earliest stages has proven to be more effective [2–4]. Dementia and cognitive decline share several common risk factors, with 21 environmental and modifiable risks identified to date, including recent evidence linking higher exposure to air pollution to these conditions [5]. Indeed, an accumulating body of research supports an adverse impact of air pollution on various cognitive outcomes.

Specifically, there is increasing evidence to indicate adverse associations between long-term exposure to particulate matter (PM) and cognitive decline or global cognitive function [6]. However, the conclusions of these studies have been inconsistent. The wide range of outcomes may stem from significant variations in cohort composition, evaluation standards, exposure characteristics, and the other factors. The evaluation standards for dimensions of cognitive function or dementia are worth discussing. In a cohort study of the Chinese Longitudinal Healthy Longevity Survey (CLHLS), it was reported that exposure to PM was a risk factor, and cognition was assessed using the Mini-Mental State Examination (MMSE) [7]. A systematic review summarized studies on air pollution and cognition, noting that most measures of cognition included memory and attention [8]. A study from the United States that included 780 old adults based their assessment of cognitive function primarily on memory and reported that cognitive function declined 53% per each 10 mg/m^3 increment of $PM_{2.5}$ [9]. Another Italian cohort study showed an association between PM_{10} exposure in 2006 and the conversion of mild cognitive impairment (MCI) to Alzheimer's disease; during the follow-up from 2008 to 2014, conversion to dementia was observed among nearly half of the subjects [10]. To date, most of studies have focused on the relationship between exposure to PM and global cognitive function, whereas limited evidence is available regarding the link between PM exposure and domain-specific cognitive function.

Concurrently, the degree of air pollution represents another significant source of variation. Most existing studies on the concentration of $PM_{2.5}$ and PM_{10}, conducted under the criteria set by World Health Organization (WHO), have focus on European and North American populations [11–15], with exposure periods typically ranging from 3 to 10 years. A system review that included four studies from Canada, the UK, the US, and Taiwan reported that every 10 mg/m^3 increase in $PM_{2.5}$ was associated with Alzheimer's disease (pooled HR: 4.82 95%CI: 2.28, 7.36) and dementia (pooled HR: 3.26, 95%CI:1.20, 5.31) [16]. In contrast, studies conducted in developing countries, where PM concentrations were significantly higher than WHO criteria, have predominantly focused on short-term exposure periods ranging from 30 days to one year. A longitudinal study based on China Health and Retirement Longitudinal Study (CHARLS) found a significant association between PM_{10} and cognitive function, using an exposure window of 60 days before the survey date [17]. Cognitive function impairment is a chronic and progressive process, making short-term exposure analyses (spanning days or months) less reliable evaluating the effects of PM. Moreover, the aging population in developing countries is climbing up, warranting greater attention to the impact of PM exposure on age-related cognitive function in these regions.

In this study, we aimed to investigate the association between PM exposure and both global cognitive function and domain-specific cognitive function in developing countries, where exposure levels to PM are significantly higher. Participants were females drawn from The Lifestyle and Healthy Aging of Chinese Square Dancer Study. This cohort is characterized by its emphasis on healthy ageing, as it fosters social support and encourages healthy behavior in line with WHO recommendations [18]. Previous studies have seldom addressed the risk factors for cognitive impairment in individuals who are relatively health.

Methods

Study population

This study population was derived from *The Lifestyle and Healthy Aging of Chinese Square Dancer Study* (registered at the WHO International Clinical Trials Registry Platform, No. ChiCTR2200056477, 2022.02.06), and Human Ethics and Consent to Participate declarations have been obtained (Wuhan University of Science and

Technology Ethics Committee, Ethics number: 202049). All the participants were recruited in 2021 from seven cities: Beijing, Shanghai, Xiamen, Chengdu, Yichang, Xiangyang, and Wuhan. Chinese Square Dance holds a special significance in representing Chinese culture, and it is a popular form of mild physical activity suitable for most people. The majority participants of Chinses Square Dance are middle-aged and older females, while male participants represent a minority. Therefore, in this study, we focused on examining the association among females. Among the original 3,162 female participants, 2,705 had clear residential information, including province, city, district (or county), and street. Subsequently, approximately 37 participants missing critical covariates information, such as BMI, alcohol consumption, smoking status etc. were excluded. As a result, this study included a total of 2,688 individuals. The inclusion and exclusion processes are presented in Figure S1.

Air pollution

We collected air pollution data from the China National Environmental Monitoring Center (http://www.cnemc.cn/en/). Data quality and validity adhered to HJ817-2018 and HJ818-2018 technical specifications. The daily 24-h mean concentration data for $PM_{2.5}$ (unit, μg/m^3), PM_{10} (unit, μg/m^3), SO_2 (unit, μg/m^3), NO_2 (unit, μg/m^3), and the maximum 8-h moving average concentrations for O_3 (unit, μg/m^3) in 2019 and 2021 were estimated based on a Random Forest (RF) model. All features were resampled at a 0.1°×0.1° resolution.

The daily concentration of each air pollutant was assigned to participants based on their residential address, including detailed residential information. Based on the daily concentration of pollutants, exposure to each participant was derived by averaging the daily concentration.

Assessment of cognitive function

All the socio-demographic characteristics, lifestyle, and disease history were self-reported by the participants in 2021. They were asked to complete a battery of face-to-face neuropsychological tests administered by trained investigators, which are reliable and valid in evaluating cognitive function. Global cognition was calculated based on four cognitive subdomains: memory, language, attention, and executive function. In brief, memory was assessed using the Auditory Verb Learn Test Version (AVLT) [19], which included two components: immediate word recall and delayed word recall. Language function was measured with the Animal Verbal Fluency Test (AFT) [20], where participants were instructed to say as many animal names as they could in one minute, with each animal name scoring one point. Attention was evaluated by the Digital Symbol Substitution Test (DSST) [21], in which participants converted nine digits into symbols in 90 s. Executive function was assessed by the Trail Making Test-B (TMT-B) [22], which required participants to connect the numbers in black and white circles in sequence as fast as they could. Composite z score was calculated by summing the sub-category z-scores of the four subdomains. In all tests, higher scores indicate better cognitive function, except for TMT-B, where a positive β indicated worse cognitive function.

Covariates

All potential confounders associated with cognitive function and cognition were selected, including socio-demographic information, lifestyle, and disease history. Individual characteristics, including age, sex, education, and marital status were obtained through a self-making questionnaire. Educational level was categorized into 0–6 years, 7–9 years, and ≥ 10 years. Marital status was classified as married and non-married. Body mass index (BMI) was calculated by dividing weight by the square of height. Lifestyle factors include smoking status, alcohol consumption, and physical activity. Smoking status was classified into current smokers and non-smokers. Alcohol consumption status was divided into current drinkers and non-drinkers. Physical activity was categorized as exceeding or meeting the recommended criterion. Hypertension was defined as blood pressure ≥ 140/90 mm Hg and/or taking anti-hypertensive medications within the past two weeks [23]. Participants with a history of diagnosed diabetes or use of glucose-lowering medications were classified as having diabetes. Participants who self-reported heart disease or stroke were identified as having cardiovascular disease. Depression was diagnosed using the PHQ-9, with depression defined as experiencing more than five symptoms in the past two weeks [24].

Statistical analyses

The data in this study were described as means with standard deviation (SDs) for continuous variables and as frequencies with proportions for categorical variables. A linear mixed model was employed to explore the association between environmental exposure and cognition, with β values and 95% confidence intervals (95% CI) estimated for each 10 μg/m^3 increase in exposure to particulate matters. Due to variations in exposure concentrations among different regions, the city where participants lived was set as random effect. To account for potential confounding factors that could influence the association between air pollution and cognition, several variables were adjusted in the models. Model 1 included adjustments for air pollutants, age, smoking status, alcohol consumption, education level, income, BMI, physical activity, depression, cardiovascular disease, hypertension, and diabetes. Recognizing that outdoor exposure to particulate matter may be accompanied by exposure to other air pollutants, a two-pollutant model was utilized in this study. Model 2 further adjusted for NO_2 based on Model 1, Model 3 adjusted for SO_2 based on Model 1, and Model 4 adjusted for O_3 based on Model 1. To investigate the relationship between particulate matter and cognitive function across different age groups, stratified analyses were conducted. The age groups were categorized as less than 60 years old, 60 to 65 years old, and higher than 65 years old.

All analyses were performed using R software (Version 4.0.3). Statistical tests were two-sided, and a P-value < 0.05 was considered statistically significant.

Results

Basic characteristics

Subjects were recruited from megacities of China and Hubei province, primarily including major cities in eastern and central China, as shown in Fig. 1. Among the seven cities, Xiangyang had the largest number of participants, totaling 1,210 participants, while Beijing had the fewest, with a total of 178 participants. All participants were dispersed and centered around the test site. PM exposure levels varied across the seven cities; specifically, the exposure levels in the coastal cities (Xiamen, Shanghai) were lower than those in the central cities (Figure S2 and S3).

The basic characteristics of the participants were presented in Table 1. A total of 2,668 older Chinese adult females were included into this study. The mean age of the participants was 61.60 ± 5.95 years, ranging from 45

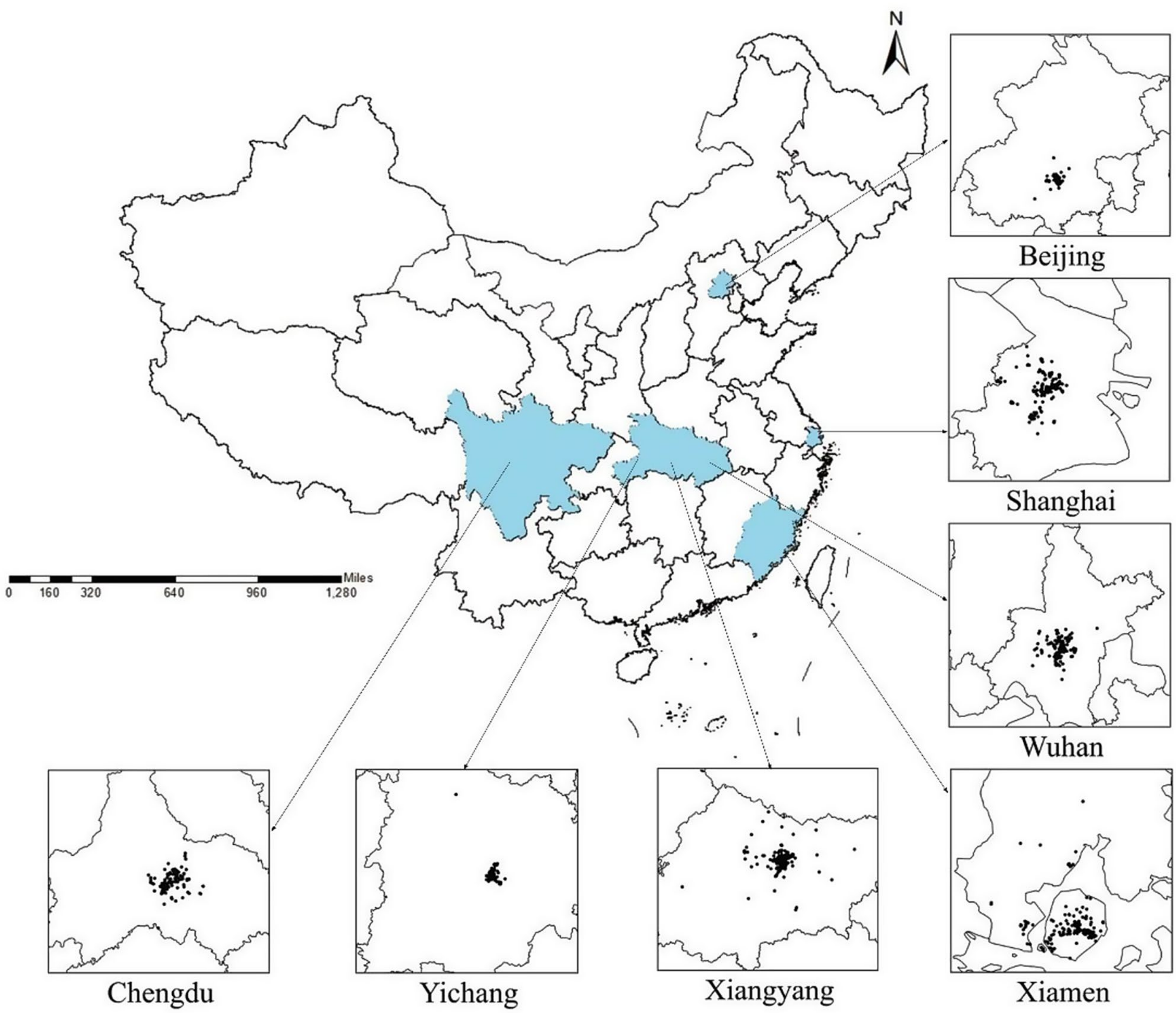

Fig. 1 Address of participants

Table 1 Descriptive characteristics of the study population

Characteristic	Overall
Age, years, mean (SD)	61.60 (5.95)
Marital status, n (%)	
Married	2277 (85.34)
Non-married	391 (14.66)
Educational Level, n (%)	
≤ 6 years	346 (12.97)
6–9 years	2013 (75.45)
>9 years	309 (11.58)
Smoking status, n (%)	
Non-smoking	2605 (97.64)
current smoking	63 (2.36)
Alcohol intake, n (%)	
Non-drinking	2351 (88.12)
Drinking	317 (11.88)
BMI, kg/m^{-2}, mean (SD)	24.10 (3.00)
Physical activity, n (%)	
Below guidelines	671 (25.15)
Meets and exceeds guidelines	1997 (74.85)
Hypertension, n (%)	1277 (47.86)
Diabetes, n (%)	246 (9.22)
CVD, n (%)	56 (2.10)
Depression, n (%)	196 (7.35)
Cognitive function score, mean (SD)	
Composite Z score	0.06 (0.71)
AVLT	0.06 (1.00)
AFT	-0.01 (1.00)
DSST	0.08 (1.00)
TMTB	-0.06 (0.94)
Air pollution, μg/m^3, mean (SD)	
$PM_{2.5}$	
one-year	36.35 (6.52)
three-year	39.45 (7.11)
PM_{10}	
one-year	75.40 (11.93)
three-year	74.07 (18.86)
NO_2	
one-year	38.85 (9.85)
three-year	28.86 (4.15)
SO_2	
one-year	9.95 (1.86)
three-year	11.18 (2.09)
O_3	
one-year	37.02 (10.43)
three-year	37.41 (6.35)

Abbreviations: SD, standard deviation; BMI, body mass index

to 82 years, with 1,078 participants being younger than 60 years old. Among all participants, 2,013 (75.45%) had completed the middle school education. Most participants (74.85%) exercised regularly and met the recommended physical activity guidelines, indicating that the study population was healthier than the general population of similar ages. Additionally, only 2.36% were current smoker, and 11.88% reported current alcohol consumption. The mean BMI was 24.10 ± 3.00 kg/m^2, and 7.35% of participants reported a history of depressive symptoms, which might be associated with cognitive function. The level of air pollutants exposure varied across participants. The mean (SD) 1-year and 3-year annual concentrations for $PM_{2.5}$ were 36.35 ± 6.25 mg/m^3 and 39.45 ± 7.11 mg/m^3, respectively, while the corresponding values for PM_{10} were 75.40 ± 11.93 mg/m^3 and 74.07 ± 18.86 mg/m^3. These concentrations of $PM_{2.5}$ and PM_{10} greatly exceeded the WHO guidelines of 5 μg/m^3 for $PM_{2.5}$ and 15 μg/m^3 for PM_{10} (WHO global air quality guidelines: particulate matter ($PM_{2.5}$ and PM_{10}), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide).

The correlation of air pollutants was presented in Table S1. All air pollutants were not highly correlated, except $PM_{2.5}$ and PM_{10}.

Association between PM concentrations and cognitive function

The association between exposure to PM and both global cognitive function and domain-specific cognitive function is presented in Table 2. In Model 1, a 3-year exposure to PM_{10} was associated with changes in domain-specific cognitive scores of DSST and TMT-B. A 10 mg/m^3 increase in PM_{10} was significantly associated with a decrease in the DSST score by -0.05 (95% CI: -0.11, 0) and an increase in the TMT-B score by 0.05 (95% CI: 0.01, 0.1). Unexpectedly, no significant association was observed between $PM_{2.5}$ exposure and either global or domain-specific cognitive function. In addition to exposure to PM, gaseous pollutants such as NO_2, SO_2, and O_3 were also present in the environment. These gaseous pollutants have been implicated in association with cognitive function, making it essential to account for their potential confounding effects. Therefore, these gaseous pollutants were adjusted for in Model 2 (NO_2), Model 3 (SO_2) and Model 4 (O_3). After adjusting for gaseous pollutants, stronger associations were observed between 3-year exposure to either $PM_{2.5}$ or PM_{10} and performance in both global cognition and specific cognitive domains. In Model 3, the 3-year exposure to $PM_{2.5}$ showed significant associations with the composite z score of global cognitive function (β = -0.15, 95% CI: -0.25, -0.04), and with specific cognitive domains, including AFT (β = -0.24, 95% CI: -0.36, -0.13), DSST (β = -0.16, 95% CI: -0.32, -0.01) and TMT-B (β = 0.16, 95% CI: 0.01, 0.32). In all models adjusted for gaseous pollutants, the 3-year exposure to PM_{10} consistently exhibited strong associations with both global cognitive function and domain-specific cognitive scores. When comparing the βs value for z scores between 3-year exposure to $PM_{2.5}$ and PM_{10}, $PM_{2.5}$ exposure yielded 2- to 3-fold higher β values for both composite z score and cognitive domains.

Table 2 Association between particulate matter exposures and cognitive function scores

Cognition	Events/ Participants	gaseous pollutants	$PM_{2.5}$		PM_{10}	
			One Year	Three Year	One Year	Three Year
Composite z score	2536/2668	Single [a]	0.03 (-0.14, 0.22)	0.04 (-0.12, 0.21)	-0.01 (-0.07, 0.06)	-0.04 (-0.09, 0.01)
		NO_2 [b]	-0.06 (-0.22, 0.09)	-0.12 (-0.33, 0.10)	**-0.06 (-0.12, -0.01) ** **	**-0.07 (-0.10, -0.03) * **
		SO_2 [c]	0.04 (-0.15, 0.22)	**-0.15 (-0.25, -0.04) ** **	-0.01 (-0.08, 0.06)	**-0.05 (-0.07, -0.04) ** **
		O_3 [d]	-0.11 (-0.34, 0.12)	-0.06 (-0.31, 0.21)	-0.05 (-0.13, 0.02)	**-0.1 (-0.18, -0.03) * **
Sub-category z-score						
AVLT	2639/2668	Single [a]	0.04 (-0.05, 0.15)	0.05 (-0.04, 0.15)	0 (-0.04, 0.05)	-0.01 (-0.03, 0.01)
		NO_2 [b]	-0.01 (-0.07, 0.05)	-0.02 (-0.08, 0.04)	-0.03 (-0.06, 0.01)	**-0.02 (-0.04, 0) * **
		SO_2 [c]	-0.06 (-0.32, 0.21)	-0.07 (-0.40, 0.26)	-0.07 (-0.17, 0.03)	**-0.07 (-0.14, 0) ** **
		O_3 [d]	0.05 (-0.06, 0.15)	-0.03 (-0.13, 0.05)	0 (-0.05, 0.05)	**-0.02 (-0.04, 0) * **
AFT	2642/2668	Single [a]	-0.01 (-0.27, 0.24)	0.01 (-0.23, 0.24)	-0.03 (-0.13, 0.07)	-0.05 (-0.13, 0.02)
		NO_2 [b]	-0.06 (-0.14, 0.01)	0.05 (-0.08, 0.17)	-0.04 (-0.08, -0.01)	**-0.03 (-0.05, 0) * **
		SO_2 [c]	0 (-0.26, 0.27)	**-0.24 (-0.36, -0.13) * **	-0.02 (-0.13, 0.08)	**-0.07 (-0.10, -0.04) ** **
		O_3 [d]	-0.08 (-0.46, 0.31)	-0.01 (-0.34, 0.31)	-0.07 (-0.19, 0.04)	**-0.09 (-0.19, 0) ** **
DSST	2583/2668	Single [a]	-0.01 (-0.21, 0.20)	0 (-0.19, 0.20)	-0.04 (-0.12, 0.04)	**-0.05 (-0.11, 0) * **
		NO_2 [b]	-0.11 (-0.26, 0.03)	-0.16 (-0.41, 0.08)	**-0.10 (-0.15, -0.04) * **	**-0.08 (-0.11, -0.04) ** **
		SO_2 [c]	-0.02 (-0.23, 0.19)	**-0.16 (-0.32, -0.01) ** **	-0.05 (-0.13, 0.03)	**-0.07 (-0.09, -0.05) * **
		O_3 [d]	-0.22 (-0.46, 0.02)	-0.04 (-0.31, 0.24)	**-0.10 (-0.19, -0.02) * **	**-0.09 (-0.16, -0.02) * **
TMT-B	2630/2668	Single [a]	0 (-0.20, 0.18)	0.01 (-0.18, 0.18)	0 (-0.09, 0.07)	**0.05 (0.01, 0.10) * **
		NO_2 [b]	0.09 (-0.05, 0.24)	0.16 (-0.06, 0.37)	0.05 (-0.01, 0.12)	**0.07 (0.03, 0.11) ** **
		SO_2 [c]	0.01 (-0.19, 0.20)	**0.16 (0.01, 0.32) * **	0 (-0.08, 0.08)	**0.06 (0.04, 0.09) * **
		O_3 [d]	0.13 (-0.12, 0.38)	0.04 (-0.20, 0.28)	0.02 (-0.08, 0.12)	**0.09 (0.03, 0.15) * **

[a] Model 1: Adjusted for age, smoking, drinking, education, income, BMI, physical activity, depression, cardiovascular disease, hypertension, and diabetes

[b] Model 2: Based on Model1, further adjusted for NO_2

[c] Model 3: Based on Model1, further adjusted for SO_2

[d] Model 4: Based on Model1, further adjusted for O_3

Notes: $*p < 0.05$, $**p < 0.01$

Additionally, in Model 2, significant associations with global cognitive function and the DSST subdomain were also observed for 1-year exposure to PM_{10}, with β values of -0.06 (95% CI: -0.12, -0.01) and −0.10 (95% CI: -0.15, -0.04), respectively.

Cognitive decline is commonly related to cerebral changes, which are often recognized as age-related processes [25]. In this study, the participants' ages ranged from 45 to 82 years old, suggesting that middle-aged population was also included. A stratified analysis based on age was conducted, grouping participants into three categories: less than 60 years old, 60 to 65 years old, and older than 65 years old. A significant association between 1-year exposure to $PM_{2.5}$ and DSST and TMT-B cognitive domains was observed in the group of older than 65 years old (Fig. 2 and S4). This association was not found in the analysis of the overall participants. The β values for the DSST and TMT-B domains were −0.21 (95% CI: -0.31, -0.10) and 0.23 (95% CI: 0.02, 0.45), respectively. Additionally, a 1-year exposure to PM_{10} associated with both global cognitive function and domain-specific cognitive function was apparently observed in the group of older than 65 years old (Fig. 3 and S5), indicating that individuals aged over 65 years were more vulnerable to PM exposure. The similar results were exhibited in 3-year exposure to both $PM_{2.5}$ and PM_{10} (Figs. 2 and 3, Figure S5). Notably, the strong association between 3-year exposure to $PM_{2.5}$ and PM_{10} and the DSST cognitive domain was consistently observed across all three age groups. This finding suggested that changes of attention function among cognitive domains might be particularly sensitive to PM exposure.

Discussion

In this study, we assessed the association between 1-year and 3-year exposure to PM and cognitive test performance in the middle-aged and older female adults. This included evaluating global cognitive function as well as four cognitive domains: memory, language, attention, and executive function. Our findings consistently showed that 3-year exposure to both $PM_{2.5}$ and PM_{10} was significantly associated with both global cognitive function and all four cognitive domains. In the stratified analysis by age, we observed that not only 3-year exposure but also1-year exposure to PM was strongly associated with both global cognitive function and cognitive domains among female individuals older than 65 years, suggesting that this age group is more vulnerable to PM exposure. Notably, among the four cognitive domains, attention function, as tested by DSST, exhibited the strongest associated with

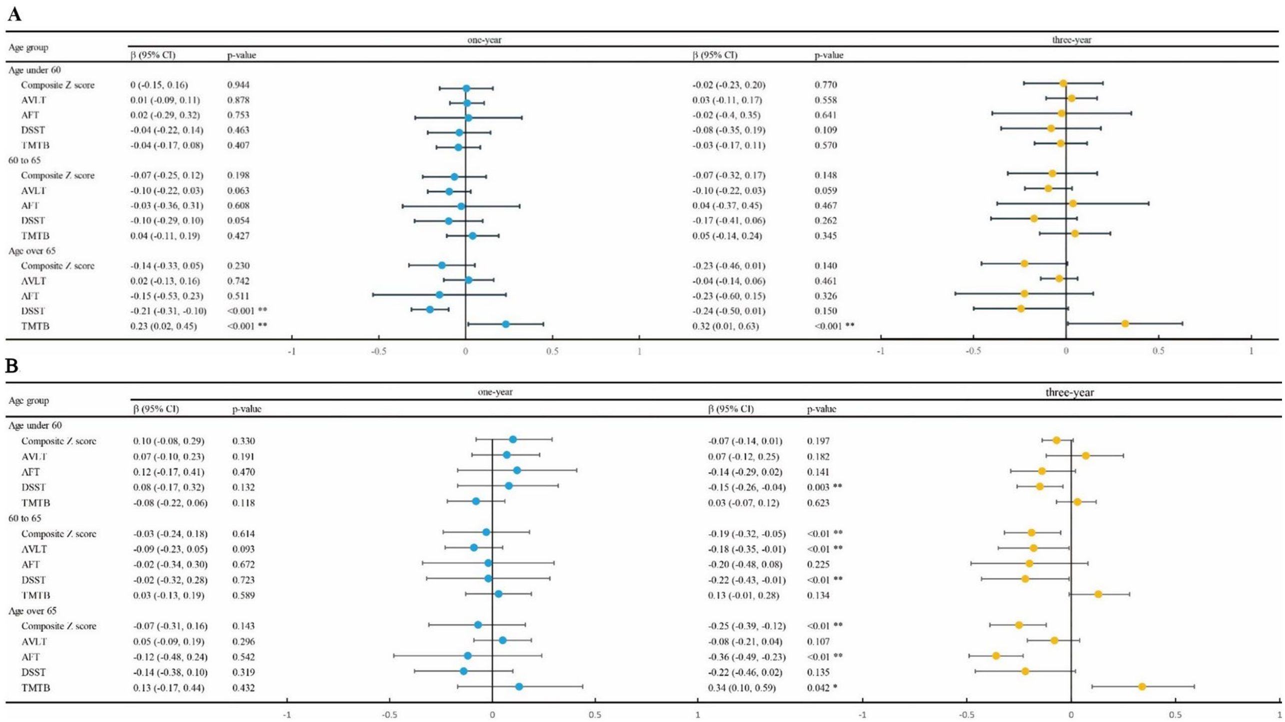

Fig. 2 **A**. βs for 1-year and 3-year average $PM_{2.5}$ and cognitive function under different age groups in model 2. **B**. βs for 1-year and 3-year average $PM_{2.5}$ and cognitive function under different age groups in model 3. Model 2: Adjusted for age, smoking, drinking, education, income, BMI, physical activity, depression, cardiovascular disease, hypertension, diabetes, and NO_2. Model 3: Adjusted for age, smoking, drinking, education, income, BMI, physical activity, depression, cardiovascular disease, hypertension, diabetes, and SO_2 Notes: *$p < 0.05$, **$p < 0.01$. Abbreviations: CI, confidence interval; $PM_{2.5}$, particulate matter with aerodynamic diameter ≤ 2.5 μm

3-year exposure to $PM_{2.5}$ and PM_{10} across the middle-aged and older female populations.

Numerous studies have documented a correlation between exposure to fine particulate air pollutants and cognitive performance, even at concentrations below WHO standards in developed countries. Most of these studies have revealed a significant association between relatively long-term exposure to PM (generally more than 3 years) and cognition [26, 27]. However, there is limited research addressing the impact of shorter-term PM exposure on cognitive function under higher pollution levels. The present study, conducted in a developing country with higher PM exposure levels, aimed to investigate the effect of PM exposure over 1-year and 3-year duration. The results indicated that 1-year exposure to PM_{10} was significantly associated with both global cognitive function and the attention function domain (measured by DSST), meanwhile 3-year exposure to either $PM_{2.5}$ or PM_{10} demonstrated pronounced associations with global cognitive function as well as all four cognitive domains (Table 2). This finding suggests that even in high PM exposure areas, longer exposure durations tend to yield more significant associations, highlighting the importance of PM exposure duration as a crucial factor for cognition. Moreover, few studies have explored the differences between varying exposure durations [28]. Given that cognitive decline leading to dementia is a progressive condition, employing multiple exposure windows provides a clearer understanding of the trajectory of neurodegenerative diseases. While abundant studies have consistently demonstrated the impact of $PM_{2.5}$ exposure on cognitive decline, research on PM_{10} remains limited and has produced inconsistent findings. For instance, one study involving 789 women reported that PM_{10} exposure was associated with visuospatial function, but no adverse associations were found with general cognitive function [29]. Similarly, another US-based study analyzed data from two prospective cohorts in the same region, assessing both $PM_{2.5}$ and PM_{10} exposure. However, cross-sectional associations were found only in the WHICAP cohort, not the other [30]. Despite participants originating from the same area, differences in exposure windows and limited spatial variability in air pollutant levels might explain these discrepancies. In present study, the PM exposure levels and durations were much higher and longer than those in the US study. Specifically, we found that 1-year exposure to PM_{10}, but not $PM_{2.5}$, was associated with global cognitive function and the attention function domain. However, for 3-year exposure, significant associations with cognitive function were observed for both $PM_{2.5}$ and PM_{10}. In this study, the β values associated with cognitive function scores resulting from PM_{10}

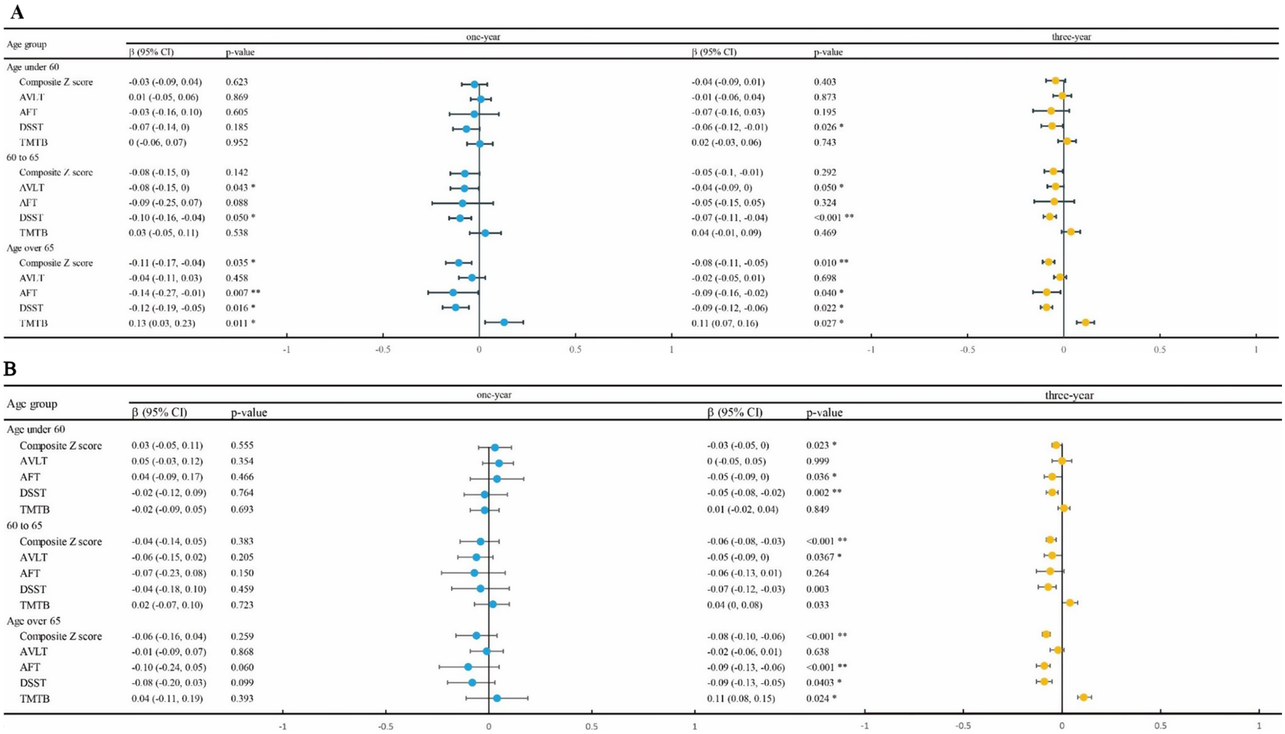

Fig. 3 **A**. βs for 1-year and 3-year average PM_{10} and cognitive function under different age groups in model 2. **B**. βs for 1-year and 3-year average PM_{10} and cognitive function under different age groups in model 3. Model 2: Adjusted for age, smoking, drinking, education, income, BMI, physical activity, depression, cardiovascular disease, hypertension, diabetes, and NO_2. Model 3: Adjusted for age, smoking, drinking, education, income, BMI, physical activity, depression, cardiovascular disease, hypertension, diabetes, and SO_2. Notes: $^*p < 0.05$, $^{**}p < 0.01$. Abbreviations: CI, confidence interval; PM_{10}, inhaled particulate matter with aerodynamic diameter ≤ 10 μm

exposure were relatively small, while those of $PM_{2.5}$ exposure were several times higher. Many previous studies have found that the impact of exposure to smaller-sized PM is consistently stronger [17, 31], which aligns with our findings. Therefore, the results of this study demonstrate logical accuracy and reliability. The individuals who participate in Chinese Square Dance tend to have better physical health compared to their peers, which may make their cognitive function less susceptible to air pollutants. Furthermore, another study also revealed that the effects of PM exposure on people with better physical health was relatively slight [31].

Another important finding of this study was the association between PM exposure and cognitive subdomains performance. A 10 μg/m^3 increase in 3-year exposure to PM_{10} was significant associated with impairments across all of four cognitive subdomains, Similarly, a 3-year exposure to $PM_{2.5}$ showed comparable results, except for the memory function domain, as measured by the AVLT (Table 2). Among the four cognitive subdomains, attention function consistently showed the strongest associations with PM exposure (Table 2; Figs. 2 and 3). The subtle differences observed among cognitive domains may be attributed to variations in particle size, which can affect different brain regions. A study using brain MRI demonstrated that while both $PM_{2.5}$ and PM_{10} exposure were significantly linked to increased cortical thickness and reduced subcortical volume in various brain regions, the susceptibility of specific brain regions varied between $PM_{2.5}$ and PM_{10} exposure [32]. Furthermore, epidemiological and animal studies have indicated that air pollutants acted as potent oxidants, capable of reaching the brain and causing neurotoxic effects [33–35]. A randomized controlled trial exposing mice to particle sample from a site near Los Angeles found that PM contributed to white matter injury [36]. Taken together, the varying susceptibility of different brain regions to PM exposure may explain the differential effects observed among cognitive subdomains.

Stratified analysis was used in current study to examine associations divided by category variables, although few studies reported on the relationship with specific cognitive subdomains [9, 17]. In this study, all participants were divided into three groups based on ages 60 and 65, as these are recognized threshold for an increased risk of developing dementia [37]. Previous studies have suggested that older adults might be more susceptible to the adverse effect of PM exposure [38]. In the current study, for both 1-year and 3-year PM exposure duration, we found that populations aged over 65 years were more vulnerable to both $PM_{2.5}$ and PM_{10} exposure. However, compared to $PM_{2.5}$ exposure, PM_{10} showed a stronger association with performance of cognitive function in this older age group. This might be because finer PM may cross the blood-brain barrier and potentially induce chronic neuroinflammation response [39]. Previous research has not identified a significant relationship between $PM_{2.5}$ exposure and hippocampal volume, while a positive association has been observed with PM_{10} exposure [32, 34, 40]. Notably, in participants aged less than 60 years, an association was observed only between attention function (but not other cognitive domains) and 3-year PM exposure. A study from Taiwan showed that early life exposure to $PM_{2.5}$ and PM_{10} were significantly increase the risk of attention-deficit/hyperactivity disorder [41], while few proof revealed the association in adults or the olds. But our study provided facts that attention function may be particularly susceptible to the adverse effects of PM exposure in adulthood. This finding aligns with the results of the overall analysis.

Our study has several strengths. First, the participants were recruited from seven major cities across China, which are representative on a national scale, making the results more robust and convincing. Second, this study accounted for co-exposure gaseous pollutants, which often occur alongside particulate matter. Few studies have addressed the co-exposure of air pollutants; however, among those that have, most reported a stronger association [42–45]. Third, we considered two exposure durations, enabling us to capture associations over different exposure periods. Fourth, in addition to global cognitive function assessments, this study evaluated domain-specific cognitive functions as well. This analysis provides more detailed insight into the associations between PM exposure and specific cognitive domains.

Besides, several limitations should be noted. First, as this is a cross-sectional study, although ambient air pollution could be assessed, changes in cognitive function over time could not be observed. Second, all participants in this study were female, which may introduce a sex bias, even though previous studies have suggested the females might be more susceptible to the adverse effect of air pollution [17]. Finally, while this study accounted for co-exposure air pollutants, we were unable to evaluate the potential confounding or interactive effects of other environmental exposures, such as temperature.

Conclusion

This study demonstrates that PM exposure is significantly associated with global cognitive function as well as all specific cognitive domains, including memory, language, attention, and executive function among Chinese females. Longer duration of PM exposure may have a stronger adverse effect on cognitive functions. Females aged over 65 years may be more vulnerable to PM exposure. Furthermore, among the four cognitive domains, attention function appears to be the most susceptible to increasing of PM exposure concentrations, even in the middle-aged population. Our findings suggest that impaired attention could serve as an early warning sign of cognitive decline and may guide policymakers in improving air pollution intervention strategies aimed at mitigating cognitive decline in aging populations.

Abbreviations

SD	standard deviation
BMI	body mass index
$PM_{2.5}$	fine particulate matter
PM_{10}	inhaled particulate matter
AVLT	Auditory Verbal Learning Test
VFT	Verbal Fluency Test
DSST	Digit Symbol Substitution Test
TMT-B	Trail Making Test-B

Supplementary Information

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Supplementary Material 1

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Author contributions

Jingling Liao (Corresponding Author): Conceptualization, supervision, Writing - Review & Editing; Jingyi Zhu and Shuaibo Wang (First Authors): Data Curation, Formal Analysis, Methodology, Writing– Original & Editing; Shuang Rong (Co-Author): Conceptualization, Supervision, Funding acquisition, Writing– Review & Editing; Peizheng Li: Software, Data Curation; Fengping Li: Data curation, Writing - Review & Editing; Benchao Li: Writing - Review & Editing; Lu Ma: Methodology, Writing - Review & Editing;

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Data availability

Our main data from The Lifestyle and Healthy Aging of Chinese Square Dancer Study, and we have not given their permission for researchers to share their data. Data requests can be made via this email: rongshuangwhu@yeah.net.

Declarations

Ethics approval and consent to participate

Human Ethics and Consent to Participate declarations have been obtained (Wuhan University of Science and Technology Ethics Committee, Ethics number: 202049). All participants gave written informed consent before enrolment in the study, which was conducted in accordance with the principles of the Declaration of Helsinki.

Consent for publication

Not applicable.

Competing interests
The authors declare no competing interests.

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