Does PM2.5 Lead To A Decline In The Cognitive Capacity of Middle-Aged And Elderly People In China?

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Research Article

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Abstract

This study investigated the relationship between PM_{2.5} concentration and the cognitive ability of middle-aged and elderly people in China using survey data from the three-phase China Health and Retirement Longitudinal Study (CHARLS), the China City Statistical Yearbooks, and PM_{2.5} data from the Columbia University International Earth Science Information Network (CIESIN). According to the constructed model, for every 1 $\mu\text{g}/\text{m}^3$ increase in PM_{2.5} concentration, the cognitive ability score of middle-aged people in China declined by 0.176 points on average. However the influence of PM_{2.5} concentration on the cognitive ability of people aged over 54 years was not significant. Physical support from children slightly improved the cognitive ability score of the middle-aged group. Education level had a significant impact on the cognitive ability of the elderly group, with those having a higher education level displaying less cognitive aging. In addition, hypertension had a significant negative impact on the cognitive ability of the elderly group.

1. Introduction

The world's population is aging, and Alzheimer's disease has become the fourth largest health hazard for elderly people worldwide. The 2018 report of the International Alzheimer's Disease Association revealed that an estimated 50 million people worldwide suffer from cognitive impairment. By 2050, this number is projected to increase to 152 million. China, as the country with the largest number of aged people in the world, is at the forefront regarding the health issues associated with aging. In association with the huge and rapidly growing elderly population in China, the number of Alzheimer's patients has exceeded 10 million. China has the most Alzheimer's disease patients in the world. The number of patients is increasing by more than 300,000 per year. There is no doubt that Alzheimer's disease will become one of the most severe health threats facing China in the future. Unfortunately, current treatments of late-stage Alzheimer's disease are not effective, so early recognition and prevention of cognitive dysfunction is critical. The factors leading to a decline in the cognitive function of middle-aged and elderly people are complex. Early research mainly focused on individual factors, such as genetic factors, health conditions, and chronic diseases. In recent years, environmental factors have also attracted the attention of researchers. Many studies in developed countries have found that long-term exposure to PM_{2.5} has a negative impact on the cognitive ability of middle-aged and elderly people. China is the world's largest developing country and has the world's second largest economy. The rapid industrialization and urbanization of China has undoubtedly resulted in a deterioration of urban air quality. Following the outbreak of haze weather nationwide in early 2013, the impact of PM_{2.5} on human health has become a significant concern among the public. PM_{2.5} may be affecting the cognitive ability of middle-aged and elderly people in China, potentially contributing to the prevalence of Alzheimer's disease. There is a need to consider how to respond more proactively to the combination of climate change and an aging population.

1 Literature review

1.1 Cognitive Impairment Of The Elderly And Measurement Methods

Alzheimer's disease, commonly known as senile dementia, is a chronic and progressive mental degenerative condition that is common in old age. Its high mortality and disability rates impose a heavy social and economic burden (Bennett DA et al., 2002). Alzheimer's disease is characterized by advanced brain dysfunction caused by chronic or progressive organic damage to the brain, and persistent and comprehensive loss of intelligence manifested in loss of memory, calculation ability, judgment, attention, and abstract thinking ability, as well as in language impairment, emotional and behavior disorders, and loss of independent living and working ability (John A. Hardy et al., 1992). The most commonly used tools for screening the cognitive ability of the elderly include the Mini-Mental State Examination (MMSE) (Folstein MF et al., 1975), which mainly tests orientation, memory, calculation ability, language skills, visuospatial ability, and attention. The Montreal Cognitive Assessment (MCA) (Nasreddine ZS et al., 2005) is mainly applied for the assessment of attention, executive ability, memory, language skills, abstract thinking, computing, orientation and other cognitive abilities in the elderly. The Clock Drawing Test (CDT) (Grober E et al., 1988) tests comprehension, planning, visual memory, the ability to reconstruct images, visuospatial function, executive function, computing power, attention, and abstract thinking. The MMSE is the most widely used of these tools for the measurement of cognitive impairment.

1.2 Relationship between PM2.5 and cognitive impairment in middle-aged and elderly people

Researchers have long been concerned about the impact of PM2.5 on the health of middle-aged and elderly people, but most of the early studies focused on the impact of PM2.5 on respiratory diseases, cardiovascular diseases, and regional elderly mortality (Endawoke Amsalu et al., 2019; Gao Ying et al., 2019; Fengping Hu et al., 2021). In the past 5 years, substantial progress has been made in research on the effects of PM2.5 on mental problems, such as anxiety, depression, powerlessness, and restless or fidgety behavior (Hejun Gu et al., 2020; Aarón Salinas-Rodríguez et al., 2018), although the evidence is still very limited. Most studies have focused on two aspects of mental illness. The first is the impact of PM2.5 on the risk of neurological diseases. Researchers have found that long-term exposure to PM2.5 significantly increases the risk of Alzheimer's and Parkinson's disease (Fu, Pengfei et al., 2019; Wu YC et al., 2015; Gabriele Cipriani et al., 2018). PM2.5 can enter the human body in a variety of ways, exerting pathological effects on the central nervous system. For example, PM2.5 can disrupt the integrity of the blood-brain barrier, making it easy for systemic inflammation to affect the central nervous system (Gabriele Cipriani et al., 2018). The olfactory nerve is another route by which PM2.5 particles enter the brain. Surprisingly, PM2.5 can also enter the gastrointestinal tract, causing a microecological imbalance in the intestines and affecting the central nervous system (Shou, Yikai et al., 2019). The second research focus has been on the impact of PM2.5 on the cognitive ability of elderly people. The results of a national health survey of retirees in the United States showed that PM2.5 exposure reduced memory and increased cognitive errors in the elderly (Jennifer A. Ailshire et al., 2014). The results of a German study on elderly women also showed that the PM2.5 concentration reduced cognitive ability and performance

of elderly women (Hejun Gu et al., 2020). In addition, some studies have found that old people with certain characteristics, such as smoking, hypertension, and obesity, are more likely to show cognitive ability deficits in association with PM2.5 (Wellenius G.A. et al., 2012; Power M.C. et al., 2015). Factors affecting the cognitive ability include age, gender, years of education, extent of disability, history of falls, hypertension, and stroke (Aarón Salinas-Rodríguez et al., 2018; Zhao Jiangang et al., 2015; Zheng Jiaying et al., 2017; Yang Yanrong et al., 2020; Yang Guang et al., 2018). However, some researchers believe that intergenerational interactions within the family is the main factor affecting the mental health of the elderly (Claire Scodellaro et al., 2012; Huang Qingbo et al., 2017).

Most of the research on PM2.5 and cognitive impairment has been conducted in developed countries, mainly focus on elderly people, with little attention paid to the middle-aged. Research from developing countries is even scarce (Jennifer A. Ailshire et al., 2014). The formation of cognitive impairment is a gradual process. To prevent the cognitive impairment of elderly people should start from paying attention to the cognitive ability of the middle-aged. Moreover, as the largest developing country in the world, China faces a difficult task in reforming its social security system and environmental protection policies due to its rapid economic growth and rapidly aging population. China is likely to face great challenges in association with cognitive impairment among the elderly, with air pollution control still being a critical issue (Fengping Hu et al., 2021). It is therefore of practical significance to explore the impact of PM2.5 on the cognitive ability of middle-aged and elderly people in China.

2. Data Sources And Model

2.1 Data sources

Data were collected from the China Health and Retirement Longitudinal Study (CHARLS), China City Statistical Yearbooks, and Columbia University International Earth Science Information Network (CIESIN). CHARLS was a large-scale nationwide survey conducted by the National Institute of Development Studies, Chinese Social Science Investigation Center, and Youth League Committee of Peking University. The respondents were middle-aged and elderly Chinese adults aged 45 years and above. The CHARLS baseline survey was carried out in 2011. In that year, and in 2013, 2015, and 2018, it was conducted in 150 counties and 450 communities (villages) in 28 provinces (autonomous regions and municipalities directly controlled by the central government). For this study, survey data were obtained for 2011, 2013 and 2015 (Table 1). A relatively high proportion of the respondents were from rural areas, and the proportion of men and women was roughly equal. The middle-aged group (45–54 years) accounted for 36.3%, 29.2%, and 23.9% of the respondents in 2011, 2013 and 2015, respectively, while the 55–64-year-old group accounted for almost 40% of all respondents in all three years. The proportion of elderly people (aged > 75 years) has gradually increased since 2011. Generally, the level of education of the interviewees was not high, with most having a primary school education or below. We also extracted data on the number of hospital beds per capita in all prefecture-level cities, and some county-level cities, from the China City Statistical Yearbook in all three survey years, to determine the medical capacity of the cities where the sampling was conducted.

Table 1
Basic survey data by year

		2011		2013		2015	
		Freq.	Percent (%)	Freq.	Percent (%)	Freq.	Percent (%)
Household type	Urban	4851	35.75	4851	35.75	4851	35.75
	Rural	8719	64.25	8719	64.25	8719	64.25
Gender	Male	6385	47.05	6385	47.05	6385	47.05
	Female	7185	52.95	7185	52.95	7185	52.95
Age (y)	45–54	4915	36.3	3952	29.2	3231	23.9
	55–64	5178	38.3	5318	39.3	5048	37.3
	65–74	2529	18.7	2984	22.1	3591	26.5
	75 and above	908	6.7	1276	9.4	1660	12.3
Education level	Illiterate	3766	27.81	3826	28.27	3850	28.44
	Primary school	5491	40.55	5444	40.23	5497	40.61
	Junior high school	2790	20.61	2769	20.46	2711	20.03
	High school and above	1493	11.03	1493	11.03	1478	10.92
Total		13570		13570		13570	

The PM_{2.5} data used in the study were derived from a gridded database of global annual PM_{2.5} concentrations (<http://sedac.ciesin.columbia.edu>) published by the Socioeconomic Data and Applications Center (SEDAC)/CIESIN. Moderate Resolution Imaging Spectroradiometer (MODIS) and Multiangle Imaging Spectro Radiometer (MISR) datasets from NASA, with geographically weighted regression (GWR), were used to predict and adjust PM_{2.5} concentrations for each grid cell. The data were converted into PM_{2.5} monitoring data in the form of raster grids. The dataset has wide coverage, high accuracy, and a high level of international recognition. According to the “secondary limit” of Ambient Air Quality Standard GB3095-2012 and related references, the PM_{2.5} concentration can be classified as very low (< 15 µg/m³), relatively low (15–25 µg/m³), low (25–35 µg/m³), slightly high (35–50 µg/m³), relatively high (50–70 µg/m³), high (70–100 µg/m³), and extremely high (> 100 µg/m³). The air quality data in all 3 years in the 124 cities involved in the CHARLS survey are shown in Table 2. In 2011, 11 of the 124 cities had extremely low daily average PM_{2.5} levels, which dropped to 9 in 2013 and then increased to 12 in 2015. In 2011, 24 of the 124 cities had a low daily average PM_{2.5} level, which fell to 22 in 2013 and then increased to 27 in 2015. The number of cities with a low concentration of PM_{2.5} was 31, 30, and 28 in 2011, 2013 and 2015, respectively. The number of cities with a slightly high concentration in

those years was 27, 29, and 16 respectively, i.e. there was a sharp drop in 2015. However, the number of cities with relatively high concentrations significantly increased in 2015. In 2013, seven cities had a high daily average PM2.5 level. We matched the PM2.5 data to city administrative areas and the number of hospital beds per capita, obtained from CHARLS, to form our data set.

Table 2
Three-year PM2.5 concentrations in 124 cities

	2011		2013		2015	
Concentration of PM2.5	Freq.	Percent (%)	Freq.	Percent (%)	Freq.	Percent (%)
Extremely low	11	8.87	9	7.26	12	9.68
Lower	24	19.35	22	17.74	27	21.77
Low	31	25.00	30	24.19	28	22.58
Slightly high	27	21.77	29	23.39	16	12.90
Higher	29	23.39	27	21.77	36	29.03
High	2	1.61	7	5.65	5	4.03
Total	124	100	124	100	124	100

We mapped the mean PM2.5 concentrations in prefecture-level cities (and above) in Chinese provinces and autonomous regions; the darker the area in the map, the higher the PM2.5 concentration. The PM2.5 concentration varied substantially among regions in China. Areas with a high PM2.5 concentration were mainly distributed in Tianjin, Hebei, Henan, Shandong, Anhui, Jiangsu, Shanghai, while areas with a low PM2.5 concentration were mainly distributed in Xinjiang, Inner Mongolia, Yunnan, Fujian, Qinghai, and Gansu. As shown in Figures1, the PM2.5 concentration was relatively high in 2011 in six regions. In 2013, the number of areas with a relatively high PM2.5 concentration increased to seven, with the addition of Shanghai, and in 2015 the number increased to eight, with the addition of Jilin. Thus, the number of areas with a high PM2.5 concentration increased over time. However the distribution of low-concentration areas was largely stable.

2.2 Analytical Framework

2.2.1. Endogeneity of the model

This study focused on whether the urban PM2.5 concentration affects the cognitive ability of middle-aged and elderly people in China. Cognitive ability in the CHARLS was measured using the MMSE, which assesses orientation, calculation, memory, and recall ability, with a maximum possible score of 21. To study the influence of PM2.5 concentration on cognitive ability, we used a general linear regression model (Model 1). However, Model 1 may have had endogenous problems, where the main independent variable,

PM2.5 concentration, may have been related to the error term. For example, PM2.5 can affect the cardiovascular and nervous system of the elderly, as a residual term. Second, many factors affect cognitive ability (dependent variable). Although the simple linear regression model included demographic variables (age, gender, education level, etc.), variables related to the health of the respondent (extent of disability, history of falls, stroke, etc.), city-level variables (number of hospital beds per capita, PM2.5 concentration), and genetic factors (IQ, etc.) are also important factors affecting the cognitive ability of middle-aged and elderly people (Insa Feinkohl et al., 2021; M.J. Armstrong et al., 2021). Also, occupation (Insa Feinkohl et al., 2021) and other important variables could not be obtained via the questionnaire. Therefore, Model 1 may omit certain important variables. Regardless of which of the above factors caused the endogenous problems, inconsistency in the ordinary least squares (OLS) estimators was observed. In this case, regardless of the sample size, the OLS estimators will not converge to the actual parameter values, so the β coefficient of PM2.5 will be biased. The simple linear regression model is expressed as follows:

$$Y = \alpha + \beta \cdot x + \varepsilon$$

where α and β are the parameters to be estimated and random error terms.

2.2.2 Selection Of Instrumental Variables

To solve the endogenous problem, a lag period in the PM2.5 concentration was introduced as the instrumental variable. This is the classic way to convert endogenous variables into instrumental ones. Historical variables are considered relatively "clean" instrumental variables. In other words, the PM2.5 concentration of the lag period is not associated with the disturbance term of the model, but is highly correlated with the PM2.5 concentration of the current period. Therefore, we used a one period lag PM2.5 concentration as the instrumental variable, and estimated it by applying two-stage least squares (2SLS) to the panel data to ensure reliability of the empirical model. The model variables are detailed in Table 3. In addition to conventional variables, such as age, education level, history of falls, smoking, and depression, exogenous explanatory variables were also included in the model, including whether the participant worked in the last week (work status), and whether they received monetary or in-kind support from their children (intergenerational interaction). The number of hospital beds per capita was also included (medical capacity).

Table 3
Model variables

Variable type	Variable name		Description
Dependent variable	Cognitive ability		Total MMSE score.
Endogenous explanatory variables	PM2.5		Calculated for each city. Unit: $\mu\text{g}/\text{m}^3$
Exogenous explanatory variables	Age		Unit: age
	Educational level (reference group = illiterate)	Primary school	1 = yes;0 = no
		Junior high school	1 = yes;0 = no
		Senior high school and above	1 = yes;0 = no
	Hypertension		1 = yes;0 = no
	Have fallen down in the past 2 years		1 = yes;0 = no
	Did you work for at least 1 hour last week?		1 = work;0 = no work
	Smoking		1 = yes;0 = no
	Depression		1 = yes;0 = no
	In-kind support from children		Unit: 100 yuan
	Monetary support from children		Unit: 100 yuan
	Number of hospital beds per capita		Calculated for each city. Unit: Zhang/100 persons
Instrumental variable	PM2.5 lag period		Calculated for each city. Unit: $\mu\text{g}/\text{m}^3$

2.2.3 Two-step Estimation Of The Iv Linear Regression Model

In the first stage of the 2SLS method, the endogenous explanatory variable (PM2.5 concentration) was subjected to an OLS regression involving the instrumental variables and all exogenous explanatory variables, to obtain a fitted value for the latent variable (PM2.5). In the second stage, cognitive ability was analyzed according to the latent variable. The obtained value and exogenous explanatory variables were then subjected to a further OLS regression. Through these two stages, β could be estimated. The model is expressed as follows:

$$\text{Firststage: PM2.5} = \delta Z_i + \theta X_i + u_i$$

$$\text{Secondstage: Cognitiveability} = \alpha + \beta * \text{PM2.5} + \gamma X_i + \epsilon_i$$

where Z_i is the instrumental variable, X_i is the exogenous explanatory variable, α , δ , θ , β , β , and γ are all parameters to be estimated, and μ_i and ϵ_i are random error terms. To compare the difference in impact of PM2.5 on cognitive ability between the middle-aged and elderly groups, the total sample was divided into two groups according to an age cutoff of 54 years (in 2015). The elderly and middle-aged groups were modeled separately; three instrumental variable models were established to analyze the impact of PM2.5 on cognitive ability.

3. Descriptive Statistical Analysis

The descriptive statistics for all variables in the overall model are given in Table 4. The models for the middle-aged and elderly groups are presented in Table 5. The maximum possible cognitive ability questionnaire score was 21 points. The descriptive statistical analysis of the main variables showed that the average cognitive ability score for all respondents across the three phases was about 10 points (Table 4), while the average scores for the middle-aged group was about 12 points; this was significantly higher than that of the total sample. The average cognitive ability score of the elderly group across the three phases was slightly lower than that of the total sample. The average age of the total sample across the three phases was about 60 years-, compared to 49 years for the middle-aged group and around 64 years for the elderly group. The average PM2.5 concentration across the three phases for the total sample was about 39 $\mu\text{g}/\text{m}^3$, with values of around 37 $\mu\text{g}/\text{m}^3$ in the middle-aged group and 39 $\mu\text{g}/\text{m}^3$ in the elderly group. The descriptive statistics of the other control variables in the overall model are shown in Table 4; the descriptive statistics by age group are not listed due to space limitations.

Table 4
Descriptive statistics for the total sample

Variable type	2011		2013		2015	
	mean	SD	mean	SD	mean	SD
Dependent variable Cognitive ability	10.677	4.403	9.967	5.148	10.355	4.550
Endogenous explanatory variables PM2.5 ($\mu\text{g}/\text{m}^3$)	37.346	16.451	40.531	19.189	38.457	18.961
Instrumental variable PM2.5 with a lag of 2 year ($\mu\text{g}/\text{m}^3$)	---	---	58.652	9.565	60.652	9.565
Exogenous explanatory variables						
Age (y)	58.652	9.565	60.652	9.565	62.652	9.565
Primary school	0.406	0.491	0.402	0.490	0.406	0.491
Junior high school	0.206	0.404	0.205	0.403	0.200	0.400
Senior high school and above	0.110	0.313	0.110	0.313	0.109	0.312
Hypertension	0.237	0.425	0.072	0.259	0.083	0.276
Fallen down in the past 2 years	0.157	0.364	0.163	0.370	0.182	0.386
Did you work last week?	0.305	0.460	0.287	0.452	0.256	0.437
Smoking	0.391	0.488	0.064	0.244	0.033	0.178
Depression	0.472	0.499	0.318	0.466	0.390	0.488
In-kind support from children	31.269	65.725	27.063	98.801	40.398	108.219
Monetary support from children	12.410	21.268	10.658	41.664	16.093	92.791
Number of hospital beds per capita	0.330	0.127	0.351	0.129	0.453	0.159

4 Results And Analysis

4.1 Results for the first stage of the IV model

The first-stage regression results of the instrumental variable model are given in Table 6. Linear regression of the endogenous variable, PM2.5 concentration, was performed, including the instrumental and exogenous explanatory variables. The instrumental variable was significant at the 0.01 level in all three models, showing that there was a strong correlation between the instrumental and endogenous variables. The correlation coefficient for PM2.5 with a lag period was negative, which may be because 2013 was a watershed year in terms of atmospheric governance in China. In that year, the State Council

issued the Action Plan for the Prevention and Control of Air Pollution, which explicitly required that, by 2017, the annual average PM10 concentration in cities at and above the prefectural level should be reduced by more than 10% compared to 2012. Beginning in 2013, many regions have established large-scale atmospheric pollution control measures. Compared to cities with better air quality, key areas such as Beijing-Tianjin-Hebei, the Yangtze River Delta, and the Pearl River Delta have enforced even stricter environmental governance policies. Policy factors may be the main reason for the negative one phase lag coefficient observed for PM2.5.

Table 5
Descriptive statistics for the main variables in the middle-aged and elderly groups

Variable name	2011		2013		2015	
	mean	SD	mean	SD	mean	SD
Middle-aged group	12.053	3.974	11.305	4.990	12.009	4.015
Dependent variable						
Cognitive ability						
Endogenous explanatory variable	36.683	17.142	39.957	19.946	37.897	19.439
PM2.5 ($\mu\text{g}/\text{m}^3$)						
Instrumental variable	---	---	36.683	17.142	39.957	19.946
PM2.5 with a lag of 2 year ($\mu\text{g}/\text{m}^3$)						
Elderly group	10.264	4.437	9.559	5.125	9.839	4.578
Dependent variable						
Cognitive ability						
Endogenous explanatory variable	37.553	16.230	40.712	18.949	38.635	18.811
PM2.5 ($\mu\text{g}/\text{m}^3$)						
Instrumental variable	---	---	37.553	16.230	40.712	18.949
PM2.5 with a lag of 2 year ($\mu\text{g}/\text{m}^3$)						

Table 6
First-stage regression results for the IV model

	Model 2 (Total sample)	Model 3 (Middle-aged group)	Model 4 (Elderly group)
PM2.5 with a lag of 2 year	-0.561*** (0.073)	-0.613*** (0.135)	-0.539*** (0.089)
Age	0.095 (0.246)	0.547 (0.658)	-0.081 (0.276)
Primary school	0.041 (2.319)	-4.200 (5.738)	0.915 (2.605)
Junior high school	-1.434 (3.390)	-5.968 (5.525)	0.690 (4.374)
Senior high school and above	13.063*** (4.643)		14.306*** (5.033)
Hypertension	-0.698 (0.992)	-1.262 (3.483)	-0.667 (1.049)
Fallen down in the past 2 years	0.892 (0.572)	0.533 (1.513)	1.038* (0.626)
Did you work last week?	1.744** (0.780)	2.881* (1.545)	1.038 (0.926)
Number of hospital beds per capita	4.552 (2.836)	4.394 (8.907)	5.15* (3.082)
Smoking	-2.89* (1.655)	-10.296 (6.891)	-2.116 (1.744)
In-kind support from children	0.005 (0.004)	0.011 (0.009)	0.003 (0.005)
Monetary support from children	0.008 (0.005)	-0.001 (0.022)	0.009 (0.006)

Note: standard error is shown in parentheses. ***, **, and * indicate significance at the 0.01, 0.05 and 0.1 levels, respectively.

	Model 2 (Total sample)	Model 3 (Middle-aged group)	Model 4 (Elderly group)
Depression	-0.355 (0.505)	-0.833 (1.106)	-0.027 (0.583)
_cons	51.342*** (13.729)	36.943 (28.615)	61.184*** (16.46)
Observations (n)	2622	640	1982
R ²	70.95%	79.1%	70.43%
Utility variable F value	58.476	20.602	36.604
Note: standard error is shown in parentheses. ***, **, and * indicate significance at the 0.01, 0.05 and 0.1 levels, respectively.			

4.2 Results for the second stage of the IV model

The regression analysis results for the second stage of the three IV models are shown in Table 7. The results for the total sample showed that PM2.5 significantly reduced cognitive ability at the 0.05 level after controlling for other independent variables. For every 1 $\mu\text{g}/\text{m}^3$ increase in the PM2.5 concentration, the cognitive ability score dropped by 0.129 points on average. Exogenous variables such as age, education level, and hypertension also had a significant impact on cognitive ability. Age was significant at the 0.01 level. With an increase in age, there was a significant decline in the cognitive ability of middle-aged and elderly people in China. To further explore the impact of PM2.5 on cognitive ability, we obtained separate models for the middle-aged and elderly groups. The second-stage regression results for Model 3 showed that, after controlling for the other independent variables, for every 1 $\mu\text{g}/\text{m}^3$ increase in the PM2.5 concentration the cognitive ability score of middle-aged people dropped by 0.176 points on average ($p < 0.05$). An increase in the PM2.5 concentration should therefore be expected to significantly reduce the cognitive ability of people aged 45–54 years in China. In addition, age remained a significant factor in Model 3. After controlling for other independent variables, when the age of middle-aged people increased by 1 year, their cognitive ability score decreased by 0.486 points on average. Intergenerational interaction significantly improved the cognitive ability of middle-aged people, with physical support from children alone slightly increasing the cognitive ability score. However, although PM2.5 was significant in Models 2 and 3, it was not significant in Model 4. After controlling for other independent variables, PM2.5 had no significant impact on the cognitive ability scores of the elderly group (aged > 54 years). Age, education level, and hypertension significantly affected the cognitive ability of the elderly participants. Age was significant at the 0.01 level in Model 4. After controlling for other independent variables, for every 1 year increase in age in the elderly group, the cognitive ability scores dropped by 0.433 points on average. A primary school education was significant at the 0.1 level, while junior middle school and senior high school education were significant at the 0.05 level; after controlling for other independent variables, the

cognitive ability of the elderly population with a primary school education was 2.958 points higher than that of illiterate elderly participants. The cognitive ability of elderly participants with a junior middle school education was 4.248 points higher than that of illiterate elderly participants, and the cognitive ability of elderly participants with a senior high school education or above was 5.045 points higher than that of illiterate elderly participants. Unlike in the middle-aged group, the influence of education level on cognitive aging among the elderly was highly significant. Older people with a higher education level displayed less cognitive aging, and the higher the education level, the longer the delay in cognitive aging. Unlike in the middle-aged group, intergenerational interaction did not have a significant effect on the cognitive abilities of the older group, although chronic diseases such as hypertension had a strong effect. Hypertension was significant at the 0.1 level in Model 4. After controlling for other independent variables, elderly participants with high blood pressure had lower cognitive scores, by 0.903 on average, than those without high blood pressure.

Table 7
Second-stage regression results for the IV model

	Model 2 (full sample)	Model 3 (middle-aged group)	Model 4 (elderly group)
PM2.5	-0.129** (-0.062)	-0.176* (-0.105)	-0.073 (-0.076)
Age	-0.405*** (-0.114)	-0.486* (-0.295)	-0.433*** (-0.130)
Primary school education	1.272 (-1.102)	-3.471 (-2.767)	2.058* (-1.200)
Junior high school education	2.028 (-1.619)	-3.303 (-2.683)	4.248** (-2.010)
Senior high school education and above	4.423* (-2.338)	.	5.045** (-2.512)
Hypertension	-0.864* (-0.472)	-0.528 (-1.659)	-0.903* (-0.484)
Fallen down in the past 2 years	0.158 (-0.275)	0.010 (-0.72)	0.179 (-0.295)
Did you work last week?	0.283 (-0.385)	1.307 (-0.798)	-0.169 (-0.432)
Number of hospital beds per capita	-0.021 (-1.364)	6.391 (-4.282)	-0.434 (-1.446)
Smoking	-0.681 (-0.798)	-4.498 (-3.454)	-0.105 (-0.81)
In-kind support from children	0.003 (-0.002)	0.010** (-0.004)	0.002 (-0.002)
Monetary support from children	0.003 (-0.003)	0.014 (-0.011)	0.001 (-0.003)

Note: standard error is shown in parentheses. ***, **, and * indicate significance at the 0.01, 0.05 and 0.1 levels, respectively.

	Model 2 (full sample)	Model 3 (middle-aged group)	Model 4 (elderly group)
Depression	0.202 (-0.242)	0.443 (-0.55)	0.269 (-0.269)
_cons	39.56*** (-8.134)	42.62*** (-15.15)	39.95*** (-10.15)
Observations (n)	2622	640	1982
R ²	25.4%	0.49%	31.59%
Note: standard error is shown in parentheses. ***, **, and * indicate significance at the 0.01, 0.05 and 0.1 levels, respectively.			

5. Conclusion And Discussion

This study comprehensively explored the relationship between PM2.5 concentration and the cognitive ability of middle-aged and elderly people in China using data from CHARLS and the China City Statistical Yearbooks, and SEDAC/CIESIN PM2.5 data. We also applied an instrumental variable method to a linear regression model to solve the endogenous problem, and to test the impact of urban PM2.5 concentration on the cognitive ability of middle-aged and elderly people. The following conclusions were obtained.

The effect of PM2.5 on cognitive ability differed between middle-aged and elderly people in China. An increase in PM2.5 concentration significantly reduced the cognitive ability score of the middle-aged group (45–54 years). After controlling for other independent variables, for every 1 $\mu\text{g}/\text{m}^3$ increase in the PM2.5 concentration, the cognitive ability score of Chinese middle-aged people dropped by 0.176 points on average. However, PM2.5 concentration had no significant effect on the cognitive ability of people aged 55 years and above.

Age had a significant impact on the cognitive ability of both the middle-aged and elderly groups. After controlling for other independent variables, for every 1 year increase in the age of middle-aged and elderly people in China, their cognitive ability score dropped by about 0.45 points on average. Level of education had a significant impact on the cognitive ability of the elderly group. Participants with higher levels of education displayed less cognitive aging, and the effect of delaying cognitive aging became more obvious as the level of education increased. In addition, the cognitive scores of elderly participants with hypertension were 0.903 points lower on average than those of the elderly participants without hypertension.

Intergenerational interaction only had a significant effect on cognitive ability in the middle-aged group. Physical support from children slightly increased the cognitive scores of this group.

The key to successful treatment of Alzheimer's disease lies in early preventive measures, starting from middle age. Our study found that people aged 45–54 years in China were more likely to suffer from cognitive impairment due to deterioration of air quality. Air pollution control is still the top priority of environmental managers in China, especially in areas with high PM2.5 concentrations. Methods for protection against PM2.5 exposure in middle-aged people should be implemented, and dynamic monitoring of the cognitive function of middle-aged and elderly people should be actively promoted. We found that the cognitive function of the well-educated elderly population in China declined slowly, but unfortunately the education level of this population in China is generally relatively low. Therefore, we suggest that community home and institutional endowment services should be used to strengthen education for this population. This could include providing elderly patients with cognitive impairment with a mild-to-moderate-intensity cognitive learning program, improving cognition via information-sharing and exchange activities, and promoting understanding of cognitive disorders among mildly affected patients and their family members.

Declarations

Authors' contributions: This paper was written by the author alone.

Competing interests: Not applicable

Ethics declarations: Not applicable

Approval for animal experiments: Not applicable

Approval for human experiments: Not applicable

Consent for publication: Not applicable

Availability of data and materials

The datasets generated and/or analysed during the current study are available in the [CHARLS] [CIESIN] [China City Statistical Yearbooks] repository, [<http://charls.pku.edu.cn/index/zh-cn.html>];

<https://sedac.ciesin.columbia.edu/data/set/sdei-global-annual-gwr-pm2-5-modis-misr-seawifs-aod/data-download>;

<http://www.stats.gov.cn/tjsj/tjcbw/index.html>]

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Figures

Figure 1

Map of PM2.5 Concentration in China (2011,2013, 2015)