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Original Research

Associations Between Air Pollution and Adults' Cognitive Decline in China

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Abstract

In the context of global aging, the decline in cognitive abilities among individuals, which can potentially worsen into dementia, poses a significant health challenge. China is a country with a high degree of population aging and severe air pollution. By applying regression analysis methods, this paper has analyzed the influence of air pollution on the cognitive decline of Chinese adults. The research results based on the China Family Panel Studies 2018 data and the China Statistical Yearbook reveal that: (1) There is a significant negative correlation between air pollution and cognitive abilities. (2) Mechanism analysis shows that air pollution indirectly affects cognitive abilities through its impact on individual depression levels, but the mediating effect of exercise on the relationship between pollution and cognitive abilities is not significant. (3) Heterogeneity analysis indicates that pollution has a greater negative impact on cognitive abilities in the younger population compared to middle-aged and elderly individuals, and it has a significant negative impact on females, urban residents, and those with healthcare. (4) The main pollutants in exhaust gases all have significant cognitive ability depreciation effects, with SO_2 being more harmful. The research results shall provide a realistic basis and a policy reference for the systematic promotion of environmental health work related to cognitive abilities.

Keywords: cognitive ability, air pollution, adult, dementia risk

Introduction

Population aging has become a serious social problem globally. With aging, older adults may experience varying degrees of cognitive decline and even develop dementia [1-3]. In the modern biomedical framework, dementia is a comprehensive syndrome characterized by cognitive impairment that significantly affects individuals' daily functioning and social interactions [4]. "Alzheimer's disease (AD)" is often used by the media to refer to a wide range of elderly dementia symptoms. China has the highest number and fastest growth rate of elderly dementia patients in the world. This poses a heavy burden on patients, families, and society. Currently, the situation of air quality improvement in China is severe, and the harm of pollution to health has become a focus of public concern [5]. It is urgent for scholars to combine these two areas and conduct interdisciplinary research, emphasizing the need to address environmental issues that affect people's health.

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The Lancet Commission report encourages investigation into the impact of air pollutants on cognitive decline at different stages of disease, particularly in preclinical AD [6].

Scholars have conducted epidemiological studies, and the results have shown that exposure to air pollution may have adverse effects on cognitive abilities [7]. Air pollution has been identified as a modifiable risk factor for dementia [6]. Existing studies suggest a correlation between particulate matter (PM) and the occurrence and progression of AD. Exposure to $PM_{2.5}$ is among the risk factors for the occurrence of AD, and exposure to PM increases hospitalization rates and the prevalence of AD [8, 9]. When air pollution levels are high, the mortality rate due to AD also increases [10]. Currently, there are some limitations in the relevant research. (1) Compared to non-environmental risk factors, research on the impact of environmental pollutants on cognitive abilities is relatively limited, and there is an urgent need for in-depth research. In addition, research from developed countries on the relationship between pollution and cognitive impairment is more extensive [11], while China's understanding of these issues is still limited and lacks sufficient attention. Neglecting the potential health effects on cognitive abilities would underestimate the overall cost of pollution. (2) Discussions on the mechanisms through which air pollution affects cognitive abilities are mostly conducted from a medical perspective [12, 13]. After the shift in cognitive research from biology to the social sciences, disciplines such as sociology and economics have the potential to provide more analysis and research on the issue. Environmental health issues involve various interdisciplinary fields, and interdisciplinary innovation is undoubtedly a crucial path to solving cognitive decline problems. (3) The existing research on pollutants and the population suffering from their impact is not comprehensive enough. While there is a focus on $PM_{2.5}$ and black carbon as the main pollutants [14, 15], there is still a lack of comprehensive discussions on the varying degrees of impact among different types of pollutants within the same literature. Currently, research mainly focuses on children, adolescents, and the elderly [16-18]. Research confirmation is needed to determine whether the associated health risks apply to a wider population.

China has transformed from being a country where the environmental disease burden was mainly associated with poverty to being a country where it is associated with pollution [19]. This study aimed to assess the influence of air pollution on the cognitive abilities of Chinese adults (≥ 18 years old). To achieve this, the researchers utilized data from the China Family Panel Studies 2018 (CFPS2018), along with matched socioeconomic indicators and air pollution data. It has been found that pollution is significantly negatively correlated with residents' cognitive abilities. Mediation analysis shows that air pollution indirectly affects cognitive abilities by influencing individuals' levels of depression. Heterogeneity analysis shows that pollution has significant negative effects on adult populations, with a greater impact on the younger population (18-35 years old) compared to the middle-aged and elderly population (≥35 years old). Air pollution mainly has significant negative effects on women, urban residents, and those with healthcare. It has negative effects on men, rural residents, and those without healthcare, but the effects are not significant. Further research has found that the three main pollutants in China's official statistics, SO_2, nitrogen oxides, and smoke and dust particles, all have significant cognitive depreciation effects. Among them, SO_2 has the greatest impact. This paper advocates for the improvement of cognitive health and pollution, which can contribute to environmental health work.

This paper has two main contributions. (1) It enriches the empirical cases and disciplinary methods of research. Due to the significant differences in pollution characteristics in different regions, the research conclusions and control strategies used in research targeting developed countries such as Europe and the US may not be directly applicable to China. The health hazards caused by pollution in China also differ significantly from those in developed countries. China's public health situation is indeed facing challenges due to its aging population and severe air pollution. These issues require more academic attention. This study utilizes comprehensive data from authoritative sources in China, involving different research levels from micro to macro, to verify the relationship between air pollution and cognitive decline. This paper also presents subtle findings from a psychological perspective, demonstrating the psychological mechanisms through which pollution affects cognitive abilities. This may inspire more interdisciplinary attention to the cognitive decline related to air pollution. (2) This paper provides an important reference value for environmental health work. The choice of pollutants is extensive, encompassing all significant pollutants found in exhaust emissions, as documented by the Chinese government. This selection has a close association with the practical efforts to reduce exhaust emissions and contributes theoretical backing and policy recommendations for the formulation of specific pollution prevention and control policies by the Chinese environmental protection authorities. The study targets all adult residents, not just the elderly. Research on cognitive abilities has already involved multiple fields, such as psychology, education, sociology, and economics. For example, economics considers cognitive abilities as an important form of human capital and also focuses on the different roles that cognitive abilities play in different stages of an individual's life cycle [20]. Therefore, it is necessary to strengthen research on both the young, the middle-aged, and the elderly populations. This research is also beneficial for the early screening and diagnosis of dementia.

Literature Review and Theoretical Hypothesis

Dementia and Cognitive Abilities

Since the 20th century, the globalization of psychiatry and the aging issue have together propelled the knowledge and practices related to diagnosing dementia into a widely influential public health topic. September is World Alzheimer's Month. Cognitive impairment is the main manifestation of AD, the etiology of which is unknown, the pathogenesis is unclear, early diagnosis is difficult, and treatment is ineffective [21]. The academic community gradually recognizes that the occurrence of AD is a continuous pathological and physiological process that goes through three stages: subjective memory decline, mild cognitive impairment (MCI), and dementia of Alzheimer's type (DAT). Cognitive impairment may start several years or even decades before the clinical stage [22]. Especially after dementia occurs, although treatment may still delay the progression of cognitive decline, the current harm cannot be undone. Therefore, targeting interventions should be carried out during the subjective memory decline stage, when the objective cognitive test scores of the elderly have not shown a significant decline yet [23]. This early intervention has the potential to delay or even prevent the progression of AD.

In early literature, there was a lack of appropriate measurement methods for human cognitive abilities. Now the operational definition of cognitive ability refers to the ability to process information, which includes the capacity of the human brain to process, store, and retrieve information [24, 25]. General cognitive abilities include sensory abilities, perceptual abilities, memory, attention, imagination, and thinking abilities [26]. They originate from fundamental physiological processes like the brain's elicited electrical potentials and reaction times in straightforward cognitive tasks. This can be comprehended as follows: the capacity to rapidly and effectively acquire relatively intricate skills influenced by external factors falls within the domain of learning ability, while the capacity to mitigate substantial adverse consequences resulting from cognitive errors falls within the realm of perceptual ability [27]. Therefore, cognitive ability is a highly generalized capacity for processing any form of complex information. It is not determined by the quantity of knowledge accumulated through learning, but rather that individuals with high cognitive abilities tend to have more knowledge as a by-product of their better understanding and faster learning. The decline in cognitive ability can lead to difficulties in instrumental activities of daily living and the loss of independent living skills [28]. It imposes a burden of diseases on individuals and society. Currently, research on cognitive ability spans multiple fields, including psychology, education, sociology, biology, and economics. Each field focuses on different aspects of cognitive ability. For example, sociologists and economists are more concerned with the important role of cognitive ability in social stratification, while biologists provide the neuroscience and brain science foundation for the aforementioned research.

Air Pollution and Cognitive Decline

Building upon the theory of health demand [29], scholars further incorporated air pollution as a factor affecting the depreciation rate of health capital, establishing a theoretical framework for the environment and health. Research conducted in recent decades has clearly shown that higher levels of air pollution have harmful effects on physiological health. Furthermore, recent studies have indicated that air pollution is also associated with some seemingly less obvious health outcomes, such as cognitive decline [30].

There is a considerable amount of research on the relationship between exposure to air pollution and cognitive test scores [31-33]. Studies on air pollution caused by traffic have shown that older adults living in areas with heavy pollution, such as areas close to major roads, have poorer cognitive abilities [34]. In addition, Yao et al. [35] analyzed the relationship between China's air quality intervention measures and the delay of cognitive decline in the elderly. Their findings confirmed that $PM_{2.5}$ not only has a causal relationship with cognitive decline in the elderly population (≥65 years old) but also accelerates cognitive aging in this population. Based on this, the first research hypothesis of this study is proposed:

H1: The more severe the air pollution, the lower the cognitive abilities.

With the increasing severity of air pollution, its impact on health inequality deserves attention. Health inequality resulting from environmental factors can be attributed to differential health effects. This term signifies that vulnerable groups experience a more pronounced impact when exposed to the same level of environmental pollution. Clifford et al. [36] found a strong relationship between air pollutants and cognitive abilities, with exposure to pollution affecting neurodevelopment in young children. Considering the heterogeneity of different countries, follow-up time, and residual confounding factors, investigating the impact of pollution on cognitive decline in different populations has become a research hot spot [37]. This not only involves the accumulation of human capital but also concerns social equity. Therefore, the second research hypothesis is proposed.

H2: The impact of air pollution on cognitive abilities in different groups varies.

Air pollution can cause neuroinflammation and other factors that can worsen the pathological burden of AD or directly damage key areas of the brain tissue. Changes in the brain's structure, like brain atrophy, could be the cause of reduced cognitive abilities linked to air pollution. Ma et al. [38] conducted a large-scale neurobiological study on AD biomarkers in China and found that the high-exposure group showed early AD pathological changes in the brain, accelerating the progression of cognitive decline. Air pollution increases the incidence of cardiovascular and cerebrovascular diseases [39], which can affect cognitive abilities in old age [40]. Furthermore, air pollution significantly increases the prevalence of overweight and obesity [41]. Overweight and obesity have been shown to have negative effects on cognitive abilities in middle-aged and elderly individuals [42]. Currently, most studies analyzing the transmission mechanisms between air pollution and cognitive abilities are explained using medical knowledge. This study attempts to empirically explore the influencing mechanisms from two perspectives. (1) From a psychological perspective, appropriate personal emotional stress can help individuals maintain a good state, resulting in higher scores in learning or cognitive tests. When individuals are depressed or under high stress, they may experience anxiety or irritability [43], which can affect brain activity [44]. Therefore, air pollution may indirectly affect cognitive abilities by influencing an individual's emotions and state. (2) From the perspective of preventing cognitive impairment-related diseases, elderly individuals who engage in exercise to maintain physical health have an effective way to prevent dementia [45]. A meta-analysis demonstrated the importance of exercise in preventing cognitive decline in the elderly [46]. Therefore, actively participating in physical exercise and other activities may partially mitigate the damaging effects. Hence, the third and fourth research hypotheses are proposed:

H3: Air pollution indirectly affects cognitive abilities by influencing an individual's emotions and state.

H4: Air pollution indirectly affects cognitive abilities by influencing an individual's exercise activities.

Current research suggests that air pollution is one of the important risk factors for AD, but the focus of each study varies. Different pollutants in exhaust gases may have varying effects on cognitive abilities [47-49]. Ma et al. [38] estimated the risk effects of three pollutants, including $PM_{2.5}$, ground-level ozone, and NO_2, at different time windows of exposure concentrations. They found that for every 20μg/m^3 increase in $PM_{2.5}$ exposure, the risk of cognitive decline increased by 10%, significantly accelerating cognitive deterioration. However, residents exposed to ozone and NO_2 were more likely to experience cognitive deterioration, but this did not reach statistical significance. Therefore, the last hypothesis is proposed.

H5: Different types of exhaust pollutants have varying effects on cognitive abilities.

Material and Methods

Samples and Data

The individual data come from the CFPS2018 dataset. The sampling of China Family Panel Studies (CFPS) follows the principles of efficiency and scientific balance, using stratified PPS sampling, with the sample size at the end expanded based on response rates. Therefore, CFPS can provide recognized, authoritative data for scholars studying resident health, including cognitive health. CFPS2018 started in June 2018, and the collected public data was fully released in December 2020. For research purposes, we selected the self-answered questionnaire section of individuals, with the age limit set at 18 and above. In this paper, samples with missing values in the main variables were excluded, and missing data for a small number of other variables was handled using missing value imputation. The final sample size of effectively surveyed respondents in the CFPS2018 is 13,177, encompassing participants from 30 provincial-level administrative regions, thereby indicating strong national representation.

The paper also draws on provincial data, mainly social, economic, and pollution indicators of the 30 provinces in 2017. The relevant data mainly came from the China Statistical Yearbook. To address endogeneity issues, we applied lagged processing to the pollution indicators. By matching each sample to the corresponding province, we achieved a matching rate of 100% between individuals and their respective provinces.

Variable Selection

The Dependent Variable

In many empirical studies, educational attainment is often used as a proxy variable for cognitive abilities due to the convenience and availability of data. However, simply using educational level as a measure often fails to comprehensively and accurately reflect the important impact of cognitive abilities on social and economic life. A typical fact is that even individuals with the same level of education can still exhibit significant differences in cognitive abilities such as reading comprehension, mathematical reasoning, and writing skills. With the development of modern psychology, measurement techniques for cognitive abilities have gradually matured. Cognitive abilities include aspects such as vocabulary, mathematical calculations, memory, attention, thinking and imagination, and logical reasoning [50-52]. However, in quantitative analysis, many aspects of cognitive abilities cannot be converted into data. Therefore, following the practice of many Chinese scholars, this paper uses the test scores from the CFPS individual cognitive module to measure individual cognitive abilities. CFPS is the first comprehensive social survey in China that measures cognitive abilities, referencing various international questionnaires. It is a more effective cognitive test scale for Chinese residents. The dependent variable (DV) is the cognitive test score, which is sourced from the cognitive module specifically included in CFPS2018. The module includes word and math tests. The higher the sum of the cognitive test scores, the higher the level of cognitive ability.

Independent Variables

The explanatory variable is air pollution, corresponding to the annual emissions of major pollutants in exhaust gases. Firstly, SO_2 is adopted as an important indicator of air pollution. In the further analysis section, this paper also discusses the effects of different types of pollutants, such as nitrogen oxides and smoke and dust particles, on residents' cognitive abilities. In 2012, the Chinese central government issued the first comprehensive plan for air pollution prevention and control. The plan explicitly states the need to deepen the control of SO_2 pollution, comprehensively carry out nitrogen oxide control, and strengthen the control of industrial smoke and dust particles. Currently, the Chinese government has strict requirements for the emission control of SO_2, nitrogen oxides, and smoke and dust particles. For example, the Ministry of Ecology and Environment proposed the goal of reducing nitrogen oxide emissions by more than 10% by 2025 compared to 2020. Local governments have also set corresponding emission reduction targets. For example, Hunan Province has proposed that the intensity of emissions of major pollutants in key industries should be reduced by 10% compared to 2022 by 2025. Therefore, the air pollution indicators in this paper can provide direct recommendations for China's air pollution prevention and control work.

Control Variables

Livingston et al. [6] proposed that 40% of dementia cases worldwide are caused by some modifiable risk factors, including air pollution, low education level, smoking, depression, and physical inactivity. Population characteristics such as age and gender may also influence research results [53]. For example, studies have shown that with increasing age, metal content in the frontal lobe increases [54], indirectly indicating an increased risk of brain damage with age. However, research focusing on different age groups of the elderly has found that residents aged 57-64 are most affected by $PM_{2.5}$ pollution [55]. By reviewing relevant literature, a series of control variables were selected for this study.

Individual variables can be divided into three types. (1) Demographic variables: gender, age, education levels, hukou (household registration), marital status, and healthcare. (2) Lifestyle and health behavior variables: smoking, sleep duration, and internet usage. (3) Physical health and medical expenses: self-assessment of memory and medical expenses. All three types of control variables are sourced from the CFPS2018 database. Among them, gender, hukou, marital status, healthcare, and smoking are dummy variables. We consider 6-10 hours/night as the standard sleep duration and treat sleep duration as a dummy variable. Age, education level, internet usage, self-assessment of memory, and medical expenses are continuous variables. Education level corresponds to the number of years of education completed by the respondent, and the amount of medical expenses is logarithmically transformed.

Provincial-level variables mainly include regional advantages, per capita GDP, GDP growth rate, and the proportion of the secondary industry in GDP. Among them, regional advantages are based on the classification of Chinese officials. The higher the number (1-3), the greater the geographical advantage of the province's region. In the eastern coastal areas of China, traditional industrialization has provided them with a path out of poverty. The central and western regions cannot follow this path, and it is also difficult for them to achieve a rapid transformation towards high-value industries and the service sector in the short term. Even within the eastern region, strengthening pollution control measures may exacerbate the current imbalance in development. These variables need to be considered in this study.

Analytic Strategies

This study utilized STATA 17.0 statistical software. Descriptive statistics were first conducted on the sample, with the studied variables presented in Table 1.

Regression analysis was then employed to estimate the impact of air pollution on residents' cognitive abilities. The regression model is as follows:

$$cong_{ij} = \alpha + \beta_1 pollution_j + \beta_2 X_{ij} + \beta_3 Y_j + \varepsilon_{ij} \quad (1)$$

Where $cogn_{ij}$ represents the cognitive test scores for resident i in province j, $pollution_j$ represents the indicator of air pollution in province j, X_{ij} represents the micro control variables of resident i in province j, Y_j represents the macro control variables of province j, and ε_{ij} represents the random disturbance term. The coefficient β_1 measures the impact of pollution on cognitive test scores.

Regarding regression models, let's start with the simple one, the variance component model (VCM). The VCM is essentially a multilevel linear regression model without any independent variable (IV). Its primary function is to decompose the sources of error at different levels, namely the error at the group level (variation between the second-level units, also known as between-group error) and the error at the individual level (variation within the first-level units, i.e., within-group error). It also calculates the proportion of between-group error to the total error (the sum of between-group error and within-group error). In real-life situations, individuals are often nested within various groups. Therefore, most survey data used in practical research has a nested data structure. However, not all quantitative studies based on nested data require the use of multilevel models. By decomposing variance components and calculating the proportion of between-group variance, another important function of the VCM is derived: to determine whether the data and variables being analyzed

Table 1. Descriptive statistics of main variables.

Variables	Observations	Mean (SD)
Dependent variable		
Cognitive ability	13177	30.204(11.275)
Independent variables		
SO_2 per capita	30	0.006(0.004)
Nitrogen oxides per capita	30	0.009(0.003)
Smoke and dust particles per capita	30	0.006(0.004)
Control variables		
Gender (male = 0)	13177	0.414(0.493)
Age	13177	40.845(13.086)
Education	13177	9.400(4.587)
Hukou (rural = 0)	13177	0.592(0.492)
Marital status (not in marriage = 0)	13177	0.801(0.399)
Healthcare (not secured = 0)	13177	0.916(0.277)
Smoking (no smoking = 0)	13177	0.357(0.476)
Duration of sleep ((<6 or ≥10 hours) =0)	13177	0.944(0.230)
Internet usage	13177	3.459(1.535)
Self-assessment of memory	13177	3.331(1.251)
Medical expenses	13177	2.356(5.415)
Region	30	2.197(0.822)
GDP per capita	30	6.061(2.793)
GDP growth rate	30	0.069(0.017)
Share of the secondary industry	30	0.409(0.063)

require statistical estimation using a multilevel model. In practical data analysis, it is possible to construct a VCM and calculate the intraclass correlation coefficient (ICC). If the ICC value is greater than 0.059, it is generally recommended to use a multilevel model for regression analysis of nested data [56].

Finally, regarding the mediation test, Baron et al. [57] define a mediator variable as a variable that lies between the IV and the DV and can transmit the influence of the IV on the DV to some extent. Now, the conditions for the existence of a mediation effect have been further simplified. For example, Zhao et al. [58] believe that it is only necessary to demonstrate that the inclusion of the mediator variable in the model leads to a decrease in the impact of the IV on the DV. This is because even without a direct effect of the IV, a mediation effect can still occur. The paper also argues that the most important test is to examine the decrease in the influence of the IV on the DV after adding the mediating variable (i.e., the indirect effect) to the model.

Results and Discussion

Baseline Regression Analysis

Table 2 presents the baseline regression results, with three models in total. Model 1 is the VCM, which displays the fully unconditional model with two levels. From the results of Model 1, the within-group standard deviation (SD) at the individual level is 11.063, and the between-group SD at the provincial level is 2.407. The ICC is 0.045, due to its value being less than 0.059, so we employed multiple linear regression.

All individual-level variables were included in Model 2. The results showed significant correlations between age ($\beta = -0.018$, $p<0.05$), education level ($\beta = 1.305$, $p<0.001$), hukou ($\beta = 0.704$, $p<0.001$), marital status ($\beta = 2.240$, $p<0.001$), healthcare ($\beta = 1.125$, $p<0.001$), internet usage ($\beta = 0.862$, $p<0.001$), self-assessment of memory ($\beta = 0.364$, $p<0.001$), medical expenses ($\beta = -0.054$, $p<0.001$), and cognitive test scores. Specifically, older individuals had lower cognitive abilities. The decline in cognitive abilities in adults as they age is known as cognitive aging [59]. Higher education levels were

Table 2. Factors influencing cognitive abilities.

Variable	Model 1	Model 2	Model 3
Gender		−0.202	−0.217
		(0.194)	(0.194)
Age		−0.018 *	−0.021 **
		(0.008)	(0.008)
Education		1.305 ***	1.285 ***
		(0.021)	(0.021)
Hukou		0.704 ***	0.696 ***
		(0.165)	(0.168)
Marital status		2.240 ***	2.174 ***
		(0.206)	(0.206)
Healthcare		1.125 ***	1.326 ***
		(0.281)	(0.281)
Smoking		−0.077	−0.068
		(0.200)	(0.199)
Duration of sleep		0.352	0.430
		(0.336)	(0.334)
Internet usage		0.862 ***	0.860 ***
		(0.063)	(0.062)
Self-assessment of memory		0.364 ***	0.367 ***
		(0.064)	(0.064)
Medical expenses		−0.054 ***	−0.049 **
		(0.014)	(0.014)
Region			0.979 ***
			(0.149)
GDP per capita			−0.259 ***
			(0.050)
GDP growth rate			−26.060 ***
			(5.578)
Share of the secondary industry			−0.304
			(1.614)
SO_2 per capita			−80.969 ***
			(21.855)
Constant		11.138 ***	13.099 ***
		(0.645)	(0.940)
Provincial level variance	2.407		
Individual level variance	11.063		
N	13177	13177	13177
R^2		0.392	0.397

Note: Parenthesized numbers mark standard error. *, **, *** indicate significance at the 5%, 1%, and 0.1% levels, respectively (the same as in the following table).

associated with higher cognitive abilities. Cognitive ability test scores were significantly higher for individuals with urban hukou compared to those with rural hukou. Muhammad et al. [60] also found that urban residents have advantages in cognitive abilities. Married individuals had higher cognitive abilities compared to those without a spouse. Having healthcare was associated with having higher cognitive abilities. People who use the internet more frequently have stronger cognitive abilities. Individuals with better self-assessment of memory had higher cognitive abilities. Higher medical expenses were associated with lower cognitive abilities.

In Model 3, provincial-level variables, including economic development and air pollution indicators, were added. The data shows that SO_2 (β = −80.969, p<0.001), region (β = 0.979, p < 0.001), per capita GDP (β = −0.259, p<0.001), and GDP growth rate (β = −26.060, p < 0.001) all have significant effects on cognitive test scores. Specifically, the coefficient of SO_2 is negative at the 0.001 significance level, indicating that air pollution significantly impairs cognitive abilities. Therefore, H1 is supported by the data. Zhang et al. [61] found that air pollution significantly hindered performance in mathematical and verbal tests. The greater the geographical advantage of a region, the higher the cognitive abilities of its people. Higher per capita GDP and GDP growth rates are associated with lower cognitive abilities among adults.

Analysis of Influencing Mechanisms

This paper attempts to explore the transmission pathway of air pollution on residents' cognitive abilities through two indirect pathways: individual emotions and state, and physical activity. Personal emotions and state are measured using the scores from the depression scale in the CFPS2018 database. Specifically, the CES-D8, which consists of 8 questions, is used, and the total score is used. The higher the score, the worse the adult's emotions and state. The exercise level is measured by the frequency of physical exercise (number of times), and the specific question in the questionnaire is, "Including physical education classes, how many times do you exercise?"

Table 3 presents the results of the mediation analysis. The level of depression, which measures personal emotions and states, significantly (p<0.01) mediates the relationship between pollution and cognitive decline, confirming H3. This aligns with the methods of intervening in cognitive impairment, which suggest that maintaining good emotions helps prevent cognitive impairment. However, the mediating effect of physical exercise is not significant (p>0.05), and H4 is not supported by the data. This may be due to the development of indoor fitness and sports in China. Firstly, there is the opening of numerous sports venues. Many sports venues have opened their doors to fitness enthusiasts in the form of free or discounted access, meeting the needs of the general public for physical exercise. Secondly, sports facilities are integrated into office areas. A new trend in sports consumption is emerging in cities, which involves indoor sports activities within office buildings. For example, popular indoor activities such as indoor frisbee competitions and table tennis matches have attracted many participants in sports consumption. These indoor activities do not have strict requirements for outdoor air quality.

Heterogeneity Analysis

This paper estimates the sample according to the following categories to explore the impact of pollution on cognitive abilities in different groups and the health inequality effect. (1) Individual characteristic differences are grouped based on age and gender. In studying the neural mechanisms of cognitive aging, including young, middle-aged, and elderly individuals, a systematic examination of the neural basis of cognitive aging throughout adulthood can provide a more accurate understanding of the timing of brain structural and functional aging. It can reveal whether brain structure and function aging occur gradually or show nonlinear changes with age during the process from youth to old age. Bookheimer et al. [62] proposed that subtle

Table 3. Results of the mediation analysis.

Mediating variables	Various types of effects	Coefficient	Bootstrap 95% CI		Is there a mediating effect?
			Lower limit	Upper limit	
Depression	Total effect	−80.969 ***	−120.139	−41.800	Yes
		(21.855)			
	Direct effect	−77.923 ***	−117.143	−38.703	
		(21.858)			
	Indirect effect	−3.046 **	−5.165	−0.928	
		(1.079)			
Exercise	Total effect	−80.969 ***	−120.505	−41.433	No
		(21.855)			
	Direct effect	−80.859 ***	−120.346	−41.372	
		(21.849)			
	Indirect effect	−0.111	−1.205	0.984	
		(0.557)			

changes in individual health often occur in middle age. According to the youth development plan formulated by the Chinese government, this paper divides the respondents into two groups: the 18-35 age group corresponds to the youth population, and the 35-year-old and above group corresponds to the middle-aged and elderly population. (2) Socioeconomic status differences are grouped based on hukou type and whether there is healthcare. Whether the respondents live in urban or rural areas and the urban-rural differences are topics that cannot be bypassed in Chinese-related research. Having healthcare reflects that the respondents' medical expenses can receive reliable official support.

In Table 4, Models 4 and 5 suggest that pollution has a greater adverse effect on the younger ($\beta = -95.117$, $p<0.01$) population (18-35 years old) compared to the middle-aged and elderly ($\beta = -56.624$, $p<0.05$) population (≥35 years old). This finding may seem somewhat unexpected, but it could reflect the gradual and continuous process of cognitive health deterioration. A continuing scholarly discussion exists regarding the onset of cognitive decline [63]. The latest survey report from official Chinese media also points out the increasing trend of younger AD patients. Screening, prevention, diagnosis, and treatment should be carried out for risk factors. Controlling and preventing air pollution can help delay or even prevent the occurrence of cognitive impairments in individuals who are currently unaffected. Models 6 and 7 indicate that, in terms of gender, air pollution has a significant negative impact primarily on females ($\beta = -124.277$, $p<0.01$), while the impact on males is not significant ($p>0.05$). The results are inconsistent with Wu et al. [9], who suggested that gender may not influence the effects of PM on cognitive abilities. One possible explanation is that the explanatory variable in Wu et al.'s study was PM, while this paper's explanatory variable is SO_2. Further research is needed to explore these factors.

The results in Table 5 indicate that air pollution has a significant negative impact on urban adults ($\beta = -128.574$, $p<0.001$ in Model 9) and those with healthcare ($\beta = -77.307$, $p<0.01$ in Model 11), while its impact on rural residents and those without healthcare is not significant ($p>0.05$). A possible explanation is that air pollution has been a typical issue in big cities in recent years [64]. Therefore, H2 is still validated. Therefore, when conducting population studies on pollution and cognitive abilities, in addition to continuously improving the observed outcomes and measurement methods of both variables, it is necessary to analyze in depth the influencing factors that may alter the empirical results and make the research as close to the actual situation as possible.

The Impact of Different Types of Pollutants

It is worth noting that different components of pollutants have different effects on cognitive abilities. Calderon-Garciduenas et al. [54] suggested that SO_2 and NO_2 in PM have subtle effects on cognitive

Table 4. Factors influencing cognitive abilities: results based on individual characteristics heterogeneity.

Variable	Model 4	Model 5	Model 6	Model 7
	Age <35	Age ≥35	Male	Female
SO_2 per capita	−95.117 **	−56.624 *	−45.554	−124.277 **
	(34.041)	(27.646)	(27.175)	(35.870)
Control variables	Yes	Yes	Yes	Yes
Constant	19.558 ***	16.161 ***	14.459 ***	12.008 ***
	(1.674)	(1.276)	(1.154)	(1.533)
N	5102	8075	7721	5456

Table 5. Factors influencing cognitive abilities: results based on different socioeconomic status.

Variable	Model 8	Model 9	Model 10	Model 11
	Rural hukou	Urban hukou	No healthcare	Healthcare
SO_2 per capita	−19.651	−128.574 ***	−125.579	−77.307 **
	(31.515)	(30.783)	(73.856)	(22.877)
Control variables	Yes	Yes	Yes	Yes
Constant	10.934 ***	15.319 ***	22.889 ***	13.539 ***
	(1.478)	(1.294)	(3.022)	(0.971)
N	5381	7796	1102	12075

abilities. Schikowski et al. [65] found that nitrogen oxides have detrimental effects on people's specific cognitive abilities, such as logical memory. The Chinese government has implemented air pollution control plans, mainly targeting SO_2, nitrogen oxides, and industrial smoke and dust particle emissions. Table 1 shows the regression results for SO_2 ($\beta = -80.969$, $p<0.001$) as an air pollutant, and this study also replaced the air pollutant indicators with nitrogen oxides and smoke and dust particles. The empirical results show that besides SO_2, the increase in per capita emissions of nitrogen oxides ($\beta = -77.512$, $p<0.05$) and smoke and dust particles ($\beta = -70.082$, $p<0.05$) also significantly negatively affect residents' cognitive abilities. However, the impact of various pollutants varies, and the statistical significance is inconsistent. Therefore, H5 is also supported by the data. This study not only confirms the conclusion in the existing literature that air pollution harms residents' cognitive abilities but also further indicates that SO_2 in exhaust gas has a stronger damaging effect.

Further Discussion

The Healthy China Action Plan (2019-2030) proposed by the Chinese government aims to reduce the growth rate of dementia in the elderly. Environmental concerns and public health are significant subjects of both theoretical and practical interest in China. Presently, the air pollution situation in developing nations like China is far from promising. Conventional interventions that focus on individuals have limited effectiveness, whereas environmental enhancements can benefit a larger segment of the population. Therefore, this study offers valuable insights into improving environmental health related to air quality.

Building a green and healthy environment for production and living is a key task in protecting the environment and people's health. Due to rapid economic development, the health problems caused by different pollution stages experienced by developed countries over the past century are concentrated in China. There is an urgent need to elucidate the mechanisms underlying health risks from pollution, as well as to clarify the patterns of pollution exposure. While environmental pollution in China has distinctive features, it is essential to create a green, safe, and healthy environment. China's economic construction has achieved historic achievements, but it has also accumulated many environmental problems, many of which have a significant impact on people's health. How can individuals maintain good physical health when exposed to prolonged air pollution? Exposure to haze can significantly increase the risk of respiratory, cardiovascular, cerebrovascular, and AD diseases. If economic development coincides with environmental degradation, the population will endure continuous smog, depriving them of access to fresh air and a habitable environment. Such a form of modernization does not align with the desires of the people. Consequently, it is imperative to prioritize efforts to improve air quality, eliminate severe pollution events, ensure access to fresh air for the population, and enhance overall well-being under clear blue skies. We should treat environmental protection as we treat human life and health and adhere to the principle of putting people's lives and health first, which is the key and driving force for protecting the environment and people's health. This study found that implementing the concept of prevention and reducing exposure to air pollutants can produce cognitive health and social benefits at the national level. National policies should move towards strengthening environmental protection and pay more attention to reducing health impacts [66].

Conclusions

China's aging population is steadily increasing, bringing with it the risk of dementia's proliferation. This has evolved into a public health concern that impacts the well-being and quality of life of the Chinese populace while also impeding sustainable economic development. This paper proposes five hypotheses. H1: The more severe the air pollution, the lower the cognitive abilities. H2: The impact of air pollution on cognitive abilities in different groups varies. H3: Air pollution indirectly affects cognitive abilities by influencing an individual's emotions and state. H4: Air pollution indirectly affects cognitive abilities by influencing an individual's exercise activities. H5: Different types of exhaust pollutants have varying effects on cognitive abilities. Among them, H1, H2, H3, and H5 are supported by data. Air pollution will significantly impair adults' cognitive abilities. The level of depression, which measures individuals' emotions and states, has a significant mediating effect on the relationship between pollution and cognitive abilities, but the mediating effect of exercise activities is not significant. The negative impact is greater in the 18-35 age group than in the 35 and above age group, and it has a significant negative impact on women, urban adults, and residents with healthcare. Further analysis of partial estimation results shows that SO_2, nitrogen oxides, and smoke and dust particles have significant cognitive ability depreciation effects, among which SO_2 has greater harm.

The effectiveness of improving China's air quality is still not stable, and the complexity and challenges of air pollution prevention and control still persist. Dementia, represented by AD, has gradually become an important issue in dealing with China's aging population. The following policy recommendations are proposed:

(1) Strengthen the special management for the environment and health. We should also comprehensively consider the various potential health effects of air pollution, such as cognitive decline. Emphasize the cognitive decline that air pollution can cause residents, incorporate pollution control into the health security system, and adjust and optimize the environmental and

health management systems and intervention systems. AD has already been included in outpatient chronic management in most parts of China, but the distribution of service resources is not balanced, and patients and their families are not satisfied with the treatment, so government attention and support are still needed.

(2) Emphasize the awareness education of the general population about the cognitive decline caused by air pollution. AD is becoming increasingly prevalent at a younger age in China, necessitating heightened attention from society as a whole to strengthen health education for the general population. The government, hospitals, public welfare organizations, the media, and other sectors of society should provide more opportunities and channels for information exchange. While enhancing public awareness of cognitive decline, more knowledge and cutting-edge information about AD prevention and treatment should also be popularized. Guide residents to pay more attention to air pollution and early cognitive screening, improve their environmental health literacy, and create a good atmosphere for public participation in cognitive health.

(3) Pay attention to the issue of unequal cognitive abilities caused by air pollution among different population groups. When we talk about "health" now, it not only involves the health of individuals but also emphasizes the health of "populations". Achieve targeted pollution control based on different genders, ages, and socioeconomic groups. From social allocation, medical systems, and other levels, maintain the cognitive health of key population groups and strengthen AD prevention, early screening, and diagnosis [67].

(4) Reduce the total emissions of air pollutants and refine the focus of control for different pollutants. The three main pollutants in China's exhaust gas, namely SO_2, nitrogen oxides, and smoke and dust particles, all have significant cognitive depreciation effects. Therefore, on the one hand, we need to coordinate control and achieve a continuous reduction in the total emissions of multiple major pollutants. On the other hand, we need to precisely target different pollutants and achieve the required emission reduction targets in key areas. Achieve a better balance between pollution prevention and control, health security, and economic development.

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Conflict of Interest

The authors declare no conflict of interest.

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