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Fine Particulate Matter Air Pollution and Cognitive Function Among U.S. Older Adults

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Objectives. There is growing interest in understanding how exposures in the residential environment relate to cognitive function in older adults. The goal of this study is to determine if neighborhood-level exposure to fine particulate matter air pollution ($PM_{2.5}$) is associated with cognitive function in a diverse, national sample of older U.S. adults.

Methods. We use cross-sectional data on non-Hispanic black and white men and women aged 55 and older from the 2001/2002 Americans' Changing Lives Study (N = 780). EPA air monitoring data were linked to respondents using census tract identifiers. Cognitive function was assessed with tests of working memory and orientation. Negative binomial regression models were used to examine the association between $PM_{2.5}$ and the number of errors on the cognitive assessment.

Results. Older adults living in areas with high concentrations of $PM_{2.5}$ had an error rate 1.5 times greater than those exposed to lower concentrations, net of individual and neighborhood-level demographic and socioeconomic characteristics.

Discussion. This study adds to a growing body of research demonstrating the importance of air pollution to cognitive function in older adults. Improvements to air quality may be an important mechanism for reducing age-related cognitive decline.

Key words: Cognition—Neighborhoods—Pollution.

POOR cognitive function can have profound social, economic, and health implications for older adults and their caregivers (Langa et al., 2008). A number of individual risk factors for low cognitive function have been identified, including lower educational attainment, less physical activity, and poor physical health (Cagney & Lauderdale, 2002; Grodstein, 2007). Environmental risk factors for cognitive function, however, have received relatively little attention in population-based studies. This is surprising considering that more than 20 years ago data from the Epidemiologic Catchment Area Study showed regional variation in the prevalence of cognitive impairment that could not be explained by individual-level characteristics (George, Landerman, Blazer, & Anthony, 1991, p.309). Although the investigators speculated that cultural and social factors underlie geographic variation in the prevalence of cognitive impairment, it is also possible that geographic differences in cognitive function reflect differential exposure to environmental hazards. For instance, emergent research suggests that exposure to outdoor air pollution may be a risk factor for declining brain health and function (Guxens & Sunyer, 2012).

Older adults are especially vulnerable to hazards in their immediate environment, and research shows that air pollution is particularly harmful to the health of older adults (Anderson, Atkinson, Bremner, & Marston, 2003). Few studies, however, have considered the link between air pollution and cognitive function in older adults. Studies of traffic-related pollution exposure show worse cognitive function among those living in more polluted areas, though these studies were limited to elderly women living in Germany (Ranft, Schikowski, Sugiri, Krutmann, & Krämer, 2009) and older residents of Boston, MA (Power et al., 2011; Wellenius et al., 2012). Of particular concern to population health is fine particulate matter ($PM_{2.5}$), a class of traffic-related particles whose aerodynamic diameter is less than or equal to 2.5 µm. Once inhaled, these small particles can cause damage to organs such as the brain (Oberdörster et al., 2004; Peters et al. 2006). For instance, Weuve and colleagues (2012) showed that older U.S. women living in areas with higher levels of $PM_{2.5}$ had more rapid cognitive decline over a 2-year period. However, Loop and colleagues (2013) did not find evidence for a relationship between $PM_{2.5}$ and incident cognitive impairment in a large sample of older U.S. men and women.

Although several studies have examined the link between cognitive function and ambient air pollution in older adults, the findings have been based on select samples or, in the case of $PM_{2.5}$, the findings have been mixed. This study examines the cross-sectional association between exposure to ambient concentrations of $PM_{2.5}$ and cognitive function in a national sample of non-Hispanic white and black men

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and women aged 55 and older. In this diverse sample of U.S. adults, we determine if older adults living in areas with higher levels of $PM_{2.5}$ air pollution have worse cognitive function.

Method

Data

This study uses data from the Americans' Changing Lives (ACL) survey, a 15-year longitudinal study of non-institutionalized U.S. adults aged 25 and older. The study sample was obtained using a stratified, multistage area probability sample with an oversampling of black adults and adults aged 60 and older. In 1986, face-to-face interviews were conducted with 3,617 respondents, representing 70% of sampled households and 68% of sampled individuals. Follow-up interviews were conducted in 1989, 1994, and 2001/2002. In 2001/2002 the follow-up interview was conducted via telephone, or in face-to-face interviews when necessary, with 1,787 respondents or their proxies (n = 95), representing 74% of the surviving baseline sample.

Although the ACL is a longitudinal study, we only use the 2001/2002 survey wave because widespread national monitoring of $PM_{2.5}$ did not begin until the late 1990s (routine data collection began at the start of 2000). We restricted our analyses to 1,077 respondents who were aged 55 years or older at the time of the survey in order to focus on the age group most at risk of having poor cognitive function (Rönnlund, Nyberg, Bäckman, & Nilsson, 2005). We omitted 87 respondents whose proxy completed the survey because the cognitive assessment was only administered to respondents who completed the interview themselves (respondents with proxies were older and more likely to have less than high school-level educational attainment). We also excluded respondents who said they moved to their current residence after 2000 (n = 45), the year in which pollution exposure was measured, or who were missing on covariates (n = 25). We limited our analytic sample to non-Hispanic whites and non-Hispanic blacks due to the small number of respondents who identified as Hispanic (n = 22) or other race/ethnicity (n = 16). In addition, we excluded 107 respondents who did not live close enough to an air monitoring station to obtain information on their area-level pollution (these respondents did not differ from the analytic sample on cognitive function or other individual characteristics). The final analytic sample consisted of 780 women and men.

Measures

Cognitive function.—In the ACL, cognitive function was assessed with a serial 3's subtraction test to measure working memory and recall of the date, day of the week, and name of the president and vice-president to measure orientation. The assessment is an abbreviated form of the Short Portable Mental Status Questionnaire (SPMSQ), which has been shown to be a reliable and valid instrument for differentiating between cognitively intact individuals and those experiencing some degree of cognitive impairment (Pfeiffer, 1975). In the serial 3's subtraction test, respondents were asked to subtract the number 3 from 20 and to keep subtracting the number 3 from each of their answers for a total of six subtractions. We created a score for the number errors on the cognitive function assessment by summing the number of errors on the four orientation items (date, day of the week, president's name, and vice-president's name) and whether any error was made on the serial 3's subtraction test. The resulting cognitive errors score ranged from 0 to 5.

Fine particulate matter air pollution.—Air pollution data was linked to ACL respondents using census tract identifiers. National tract-level pollution measures were derived from data collected in the Environmental Protection Agency's Air Quality System (AQS), and made available for public use from RAND's Center for Population Health and Health Disparities (Escarce, Lurie, & Jewell, 2011). Pollution levels for each respondent were calculated based on air monitoring data from AQS monitoring sites within a 60-km radius of the respondent's tract centroid. A review of research on local spatial variation in air pollutants concluded that the spatial distribution of fine particles is fairly uniform; several studies have found values of $PM_{2.5}$ recorded at monitoring sites to be in good agreement with values recorded at individual residences (Monn, 2001). Tract-level $PM_{2.5}$ should, therefore, provide a reasonable approximation of levels at individual residences.

We use data on annual $PM_{2.5}$ levels in the year 2000 for this study. An annual average measure of $PM_{2.5}$ was derived for each tract using daily monitoring data recorded at monitoring sites around the U.S. Site-specific quarterly measures of $PM_{2.5}$ were derived by computing an unweighted average of daily $PM_{2.5}$ concentration on each day for which a 24-hr daily mean was recorded. Daily monitor values were aggregated to create a monitor-specific annual average. The following inverse distance formula was used to obtain the average $PM_{2.5}$ concentration for each census tract based on data from monitors within a 60-km radius of the census tract centroid:

$$Z_p = \frac{\sum_{i=1}^{n} Z_i W_i}{\sum_{i=1}^{n} W_i}$$

where Z_p represents the interpolated $PM_{2.5}$ value at the respondent's census tract centroid, Z_i is the monitor-specific annual mean of $PM_{2.5}$, W_i is the inverse distance function (1/distance from tract centroid to monitor i), and n is all monitors within a 60-km radius of the respondent's tract centroid.

Covariates.—Individual sociodemographic characteristics include age, gender, race, education, income, and marital status. Age is measured with categories representing those aged 55–64 (reference category), 65–74, 75–84, and 85 and older. We use dichotomous indicators for female gender and black race. Education is dichotomized to distinguish between those with less than 12 years of education and those with 12 or more years of education (reference category). Annual household income is the total reported pretax annual income of the respondent and his/her spouse/partner in 2001/2002. Income was fully imputed for $n = 95$ respondents and imputed within reported income brackets for $n = 185$ respondents (34% of analytic sample). Imputed income values were generated using the sequential regression imputation method in IVEware (Raghunathan, Lepkowski, Van Hoewyk, & Solenberger, 2001). Marital status is categorized to distinguish between those who are not married and those who are currently married (reference category).

We also include employment status and residential tenure in our analyses to account for differential exposure to pollution in the neighborhood environment. We categorize current employment status into currently working (reference category), retired, and unemployed. The unemployed category consists primarily of those who have a disability and those who identify as homemakers. Individuals who are long-term residents of the neighborhood may have greater cumulative exposure to neighborhood pollution. Thus, models also include a measure for residential tenure, which is the total number of years lived at the current residence.

Air pollution levels are higher in socioeconomically disadvantaged neighborhoods (Ash & Fetter, 2002), and thus neighborhood $PM_{2.5}$ may serve as a proxy for the influence of neighborhood social and economic conditions on cognitive function. In order to determine if $PM_{2.5}$ is associated with cognitive function independent of other neighborhood conditions, we include tract-level measures of neighborhood socioeconomic disadvantage and affluence from the 2000 Census. Neighborhood socioeconomic disadvantage is a standardized scale ($\alpha = .91$) consisting of the following items: percent of households on public assistance, percent of persons with below poverty-level income, and the adult unemployment rate. Neighborhood affluence is a standardized scale ($\alpha = .88$) consisting of the percent of adults aged 25 and older with at least 16 years of education and the percent of professionals and managers in the tract.

Analytic Strategy

The primary goal of the analysis is to determine if there is an association between $PM_{2.5}$ and the number of errors on the cognitive function assessment, net of individual and neighborhood characteristics. The variance exceeds the mean for the cognitive errors score because most respondents made zero errors. This suggests the data are over-dispersed and that a negative binomial model should be used. Negative binomial models are a generalization of Poisson models for count data, but a likelihood ratio test suggested the negative binomial model is more appropriate than the Poisson model. As there was minimal tract-level clustering in our data (less than 1.4 respondents per tract), we chose to use single-level regression models (Clarke, 2008) with a robust variance estimator that yields robust standard errors that account for within-cluster correlation. Sample weights are used in all analyses to adjust for differential sampling probabilities and nonresponse. Analyses were conducted using STATA Version 12.

Results

Table 1 shows descriptive statistics for the sample. The sample was approximately evenly split among those under age 65 and those aged 65 and older. Women constituted 61% of the sample and about 10% of respondents were black. Most respondents reported having at least 12 years of education, with only 22% reporting less than 12 years of schooling. The average annual household income was about $35,000. Half of the respondents reported not being married and most respondents were not working. On average, respondents had lived at their residence for nearly 23 years and lived in neighborhoods with below average levels of disadvantage and slightly above average levels of affluence. The average $PM_{2.5}$ concentration in areas where respondents lived was $13.8\mu/m^3$. The national ambient air quality standard, which is determined by the EPA to be the level at which there is increased risk to human health, is 12 µg/

Table 1. Descriptive Statistics, ACL (2001/2002) Age 55+ ($N = 780$)

Variables	Mean (*SD*)/%
Individual-level variables	
Cognitive errors (0–5)	0.52 (0.8)
Age	
55–64	49%
65–74	25%
75–84	19%
85+	7%
Female	61%
Black	10%
Education	
<12 years	22%
12 years	37%
>12 years	41%
HH income, $	35,000 (87,000)
Not married	50%
Employment status	
Employed	33%
Unemployed	21%
Retired	46%
Residential tenure, years	22.7 (15.4)
Neighborhood-level variables	
$PM_{2.5}$ (µg/m^3)	13.8 (3.1)
Neighborhood disadvantage	−.23 (0.7)
Neighborhood affluence	0.07 (0.9)

Note. ACL = Americans' Changing Lives; HH = household; PM = particulate matter; SD = standard deviation.

m^3 for $PM_{2.5}$. Nearly two-thirds of the respondents lived in areas where $PM_{2.5}$ exceeds the air quality standard.

Figure 1 shows the association between the cognitive errors score and key predictors of cognitive function. Each horizontal bar represents the incident rate ratio (IRR) and the 95% confidence interval (95% CI) for each covariate from a weighted negative binomial regression of the count of errors. The rate of errors increased with age, was higher among blacks and those with low education and income, and increased with greater functional limitations.

Results from negative binomial regression models of the association between neighborhood $PM_{2.5}$ and the count of cognitive errors are shown in Table 2. IRRs are presented (with 95% confidence intervals in parentheses). IRRs between zero and one indicate lower error rates; ratios greater than one indicate greater error rates. We divided $PM_{2.5}$ values by 10 so a one-unit increase in $PM_{2.5}$ represents a change from a low pollution environment (e.g., 5.0 μg/m^3) to a high pollution environment (e.g., 15.0 μg/m^3).

Model 1 examines the unadjusted association between $PM_{2.5}$ and cognitive errors. The results show that those living in areas with high pollution exposure had an error rate 1.7 (IRR = 1.69 [95% CI, 1.10–2.59]) times greater than those living in low pollution environments. Model 2 shows the association between $PM_{2.5}$ and cognitive function is reduced, but remains statistically significant ($p < .05$), after accounting for key individual and neighborhood-level characteristics. Those living in areas with greater exposure to $PM_{2.5}$ had an error rate 1.5 times greater than those exposed to lower $PM_{2.5}$ concentrations (IRR = 1.53 [95% CI, 1.02–2.30]). To put the difference in exposure to low–high pollution environments in context, the error rate of those with only 12 years of educational attainment was 1.5 times greater than those with more than 12 years of completed education (IRR = 1.52 [95% CI, 1.10–2.12]). To check the robustness of our results, we also estimated Model 2 with additional covariate adjustments for factors that may lead to poor cognitive function, including body mass index, physical activity, smoking status, chronic diseases such as stroke and hypertension, and neighborhood characteristics such as social disorder and older age composition. Our findings were unchanged with additional model adjustments.

Conclusion

Previous research on cognitive function in older adults has highlighted the importance of the residential environment. Most existing research has focused on the role of the social environment, highlighting factors such as poverty and social amenities (Aneshensel, Ko, Chodosh, & Wight, 2011; Clarke et al., 2011; Hazzouri et al., 2011; Lang et al., 2008; Sheffield & Peek, 2009; Wight et al., 2006). Our findings provide compelling evidence that the physical environments in which individuals age matter as well. The results of this study suggest there is an adverse effect of exposure to $PM_{2.5}$ on cognitive function among older adults. Our findings are consistent with previous research linking traffic-related and particulate matter air pollution to cognitive function in older adults (Power et al., 2011; Ranft et al., 2009; Wellenius et al., 2012; Weuve et al. 2012). However, this is the first study, to our knowledge, to demonstrate an association between air pollution and cognitive function in a racially diverse sample of older U.S. men and women.

There is growing concern over the adverse health effects of $PM_{2.5}$. Living in areas with high levels of air pollution has been linked to markers of neuroinflammation and neuropathology that are associated with neurodegenerative conditions such as Alzheimer's disease (Calderón-Garcidueñas

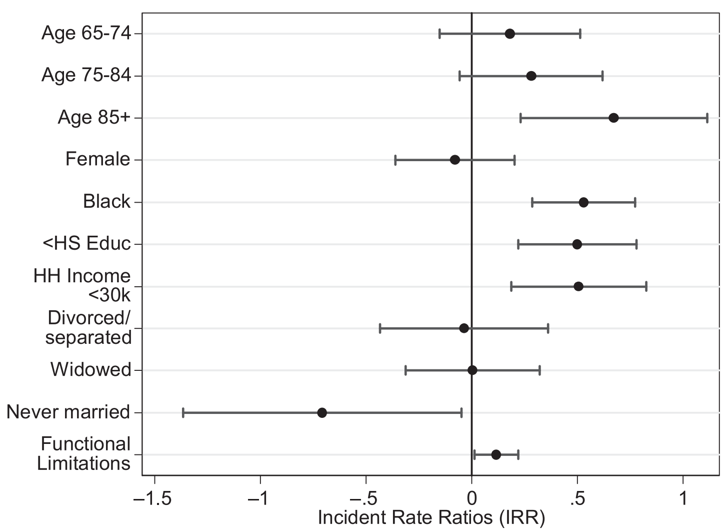

Figure 1. Characteristics associated with count of cognitive errors in ACL (2001/2002) among respondents aged 55+. IRRs from weighted negative binomial regression of count of cognitive errors. References category is age 55–64, male, non-Hispanic white, HS+ education, HH income 35k+, married, zero functional limitations. ACL = Americans' Changing Lives; HH = household; HS = high school; IRR = incident rate ratio.

Table 2. Negative Binomial Regression of Count of Errors on Cognitive Function Questions, ACL (2001/2002) Age 55+ (*N* = 780)

	Model 1		Model 2	
	IRR	(95% CI)	Odds ratio	(95% CI)
$PM_{2.5}$, 10 μg/m³ increment	1.69*	(1.10,2.59)	1.53*	(1.02–2.30)
Age				
55–64 (reference)				
65–74			1.14	(0.83–1.57)
75–84			1.32+	(0.95–1.84)
85+			2.12***	(1.42–3.17)
Female			0.95	(0.74–1.22)
Black			1.69***	(1.30–2.18)
Education				
>12 years (reference)				
12 years			1.52*	(1.10–2.12)
<12 years			2.15***	(1.50–3.10)
HH income			0.99*	(0.99–1.00)
Not married			0.92	(0.82–1.04)
Employment status				
Employed (reference)				
Unemployed			1.34	(0.90–1.98)
Retired			1.35	(0.93–1.94)
Residential tenure, years			0.99+	(0.99–1.00)
Neighborhood disadvantage			0.92	(0.80–1.07)
Neighborhood affluence			0.82*	(0.68–0.99)
Constant	0.25***	(0.13,0.48)	0.18***	(0.09–0.38)
α (overdispersion parameter)	0.46*	(0.24,0.89)	0.03+	(0.00–7.49)
Log likelihood	−611.84		−553.00	

Notes. ACL = Americans' Changing Lives; CI = confidence interval; HH = household; HS = high school; IRR = incident rate ratio; PM = particulate matter.
$***p < .001$; $**p < .01$; $*p < .05$; $+p < .10$.

et al., 2004; Levesque, Surace, McDonald, & Block, 2011). The current study adds to the growing biological and social scientific evidence supporting the importance of exposure to air pollution in brain aging.

There are some study limitations worth noting. The ACL cognitive screen is an abbreviated SPMSQ and lacks some of the components of cognitive assessments thought to capture cognitive function and impairment, such as word recall tasks to assess memory, that are used in other national surveys of older adults (e.g., Aneshensel et al., 2011; Clarke et al., 2011). However, the measure we use in this study contained assessments of working memory and orientation, which are thought to represent some of the earliest signs of cognitive loss (Ashford et al., 1990; Herzog & Wallace, 1997). Furthermore, our measure of cognition related to individual demographic, socioeconomic, and health characteristics in ways similar to what has been shown in other studies of cognition in older adults (Aneshensel et al., 2011; Clarke et al., 2011; Hazzouri et al., 2011; Lang et al., 2008; Sheffield & Peek, 2009; Wight et al., 2006).

We use a neighborhood-based measure of pollution that may not fully capture individual exposure. Although residential outdoor pollution levels may be an important contributor to overall exposure to air pollution, exposure may also occur in other contexts, such as in the workplace or during daily road travel. However, older adults are more likely to be retired and spend more time in and around their homes on a daily basis so a neighborhood-based measure may be a good approximation of their pollution exposure. More importantly, levels of $PM_{2.5}$ are higher near major roads and freeways, and our measure may not capture this variability. Although there is a growing emphasis on using model-based methods to estimate pollution exposure (e.g., kriging), simpler measurement methods, such as that used in this study, are still useful for assessing pollution effects, and are more feasible when research questions are at a formative stage and etiologic effects are still under investigation (Jerrett, 2005). However, more complex exposure assessments will be required as the focus shifts from establishing a relationship between air pollution and cognitive function to determining accurate effect sizes.

Ideally, we would want long-term, individual-level pollution exposure data to assess the importance of $PM_{2.5}$ for cognitive function. However, in the absence of such data, our measure likely captures, at least to some extent, longer-term, personal exposure. For instance, although we use year 2000 $PM_{2.5}$, levels of particulate matter pollution are highly correlated over time. Weuve and colleagues (2012) found correlations of .98 and .94 between $PM_{2.5}$ measured in a given year and levels measured 1 and 4 years prior, respectively. They also found a .89 correlation with estimated levels of $PM_{2.5}$ in 1988 (based on 1998 levels of PM_{10}). In the 2001/2002 survey, about 75% of ACL respondents reported living at their residence for at least 10 years (and 55% for at least 20 years), so it is likely that 2000 levels of $PM_{2.5}$ reflect both current and longer-term exposure. Previous research also finds high correlations between outdoor and personal levels of $PM_{2.5}$, and between outdoor and indoor levels (Monn, 2001). Thus, even though we use an ambient measure of $PM_{2.5}$, we are also likely to be measuring personal exposure as well.

Although this is the first study to examine the link between neighborhood air pollution and cognitive function using data from a national sample of both older men and women, our sample represents a select group of older adults who survived from the baseline interview in 1986 to the 2001/2002 interview. Thus, our sample may be healthier than the older U.S. population because less healthy respondents died or were lost to follow-up over the course of the study. In addition, because we excluded older adults who were institutionalized or had proxy-assisted interviews, the study findings are somewhat biased toward a cognitively intact older adult population. Thus we do not know how $PM_{2.5}$ relates to cognitive function among older adults who have considerable cognitive impairment.

Another study limitation is that we were only able to assess cross-sectional associations between neighborhood air pollution and cognitive function and were unable to determine the effects of long-term exposure to air pollution on cognitive function. Although year-to-year air pollution levels are highly correlated, neighborhood pollution may have been very different in previous decades. Pollution may have increased in some areas due to industrial and population growth, and the new major roads and freeways that accompany such growth, while in other areas pollution may have fallen with declines in industry and population. Unfortunately, monitoring of $PM_{2.5}$ did not begin until the end of the 1990s and thus we have no way to determine lifetime exposure to this particular pollutant for existing cohorts of older adults. Although this study shows preliminary evidence that exposure to air pollution may contribute to cognitive function in older adults, future studies should consider the life course context in which individuals age, particularly with respect to environmental factors

Finally, we included a number of potentially important confounding factors in the analytic models and examined the robustness of our findings to further adjustments in sensitivity analyses. However, we were unable to control for several other potentially important confounders, such as diet and cognitive engagement, which are thought to be key risk factors for poor cognitive function in old age.

Despite these limitations, the current study adds to the emerging gerontological literature identifying environmental risk factors for poor cognitive function. Much of the existing research has focused on the developing brain in younger populations, but air pollution may have consequences for the aging brain as well. Air pollution exposure may represent an important modifiable risk factor for poor cognitive function in older adults.

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J. A. Ailshire planned the study, conducted the data analysis, and wrote the paper. P. J. Clarke assisted in interpreting the data and contributed to revising the paper.

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