International Journal of Hygiene and Environmental Health 264 (2025) 114521

Contents lists available at ScienceDirect

International Journal of Hygiene and Environmental Health

journal homepage: www.elsevier.com/locate/ijheh

Neighborhood environment and cognitive functioning in middle-aged and older population: A mediating role of physical activity

A. Dalecká [a], A. Kšiňan [a], D. Szabó [a], N. Čapková [b], H. Pikhart [a,c], M. Bobák [a,c,*]

[a] RECETOX, Faculty of Science, Masaryk University, Brno, Czech Republic
[b] National Institute of Public Health, Prague, Czech Republic
[c] Institute of Epidemiology & Health Care, University College London, London, United Kingdom

ARTICLE INFO

Keywords:
Cognitive function
Ambient air pollution
Greenness
Socioeconomic deprivation
Physical activity

ABSTRACT

Background: Evidence on the impact of complex neighborhood environment, including air pollution, greenness, and neighborhood socioeconomic deprivation (nSED) on cognitive health in older adults remains scarce. Both cognition and neighborhood environment are associated with physical activity, but little is known about the potential mediating role of physical activity in this association.
Methods: Cross-sectional data of the Czech arm of the HAPIEE cohort study examined 4,178 participants (55.6% women) aged 45–69 years. Global cognitive score was constructed from memory, verbal fluency, and concentration domains. The exposures, assigned to participant's addresses, include 4-year (2000–2003) average concentrations of $PM_{2.5}$, greenness index calculated from tree crown canopy cover estimation (2000), and census-based nSED characteristics. Physical activity and other covariates were assessed by a questionnaire. Structural equation modelling was used to estimate standardized β coefficients for the relationships between neighborhood environment, physical activity and cognitive performance.
Results: After controlling for a range of covariates, global cognitive function was inversely associated with $PM_{2.5}$ ($\beta = -0.087$; 95%CI: 0.122 to -0.052) and nSED ($\beta = -0.147$; 95%CI: 0.182 to -0.115), and positively associated with greenness ($\beta = 0.036$; 95%CI: 0.001 to 0.069). We identified a weak but statistically significant mediating role of physical activity in the associations of $PM_{2.5}$ exposures and nSED on global cognitive score. Total mediation proportions ranged from 3.9% to 6.5% for nSED and $PM_{2.5}$, respectively.
Conclusions: The neighborhood environment was associated with cognitive health in older individuals; the associations were partially mediated by physical activity.

1. Introduction

As the proportion of the elderly population (over 60 years) worldwide is indicated to nearly double from 12% to 22% in 2050 (Przedborski et al., 2003), it is crucial to understand the fundamentals of healthy aging. Cognitive health is among the major factors underlying good quality of life of older people, as it enables them to maintain a sense of purpose and the ability to live independently (Przedborski et al., 2003; Clare et al., 2017). The proportion of people with cognitive impairment is estimated to triple by 2050, posing a high socioeconomic burden worldwide (Vaupel, 2010; World Health Organization, 2015).

Cognitive functioning may be negatively affected by number of personal, behavioral and biological factors such as age, sex, education, excessive alcohol drinking, social isolation, and range of cardiometabolic and cerebrovascular risk factors (Campbell et al., 2013; Wu et al., 2020; Fabbri et al., 2016). In particular, physical activity has been recognized as an effective intervention for the prevention of cognitive decline and neurodegenerative diseases in older populations, with significant positive effect of physical activity on global as well as domain-specific cognition, including processing speed, memory, and executive function, and, less consistently, on attention and motor functions (Liegro et al., 2019; Niederer et al., 2011; Hillman et al., 2008; Lees and Hopkins, 2013; Iso-Markku et al., 2024; Bos et al., 2014). The protective effect of physical activity on the cognitive function of the elderly may be explained by several direct and indirect mechanisms. Physical activity improves brain health directly by enhancing supramolecular mechanisms (e.g., neurogenesis, synaptogenesis, and angiogenesis), neuroplasticity, functional connectivity of the hippocampus,

* Corresponding author. Institute of Epidemiology & Health Care, University College London ,1-19 Torrington Place, London, United Kingdom.
E-mail address: m.bobak@ucl.ac.uk (M. Bobák).

https://doi.org/10.1016/j.ijheh.2025.114521
Received 1 October 2024; Received in revised form 17 December 2024; Accepted 8 January 2025
Available online 13 January 2025

and increasing grey matter volume (Lista and Sorrentino, 2010; Ma et al., 2017; Aly and Kojima, 2020). Importantly, physical activity has well-established effect on reducing cardiometabolic and cerebrovascular risks, preventing psychological stress and depression, and promoting social inclusion (Zhang et al., 2020; Pearce et al., 2022; Cheng et al., 2018).

In contrast to physical activity, neighborhood environment, including air pollution, greenness, and unfavorable neighborhood socioeconomic characteristics, were found to determine brain health (Hüls et al., 2018; Zaninotto et al., 1978; Wu et al., 2015a). Ambient air pollution, specifically particulate matter with aerodynamics of less than 2.5 μm ($PM_{2.5}$) has been identified by the World Health Organization (WHO) and European Environmental Agency (EEA) as a key environmental human health concern (European Environmental Agency, 2022; World Health Organization, 2021). Previous systematic reviews and meta-analysis have suggested that long-term exposure to air pollution is associated with impaired cognitive functions (Zhao et al., 2021a; Schikowski and Altuğ, 2020; Delgado-Saborit et al., 2021; Thompson et al., 2023); however, the effect on specific cognitive domains such as memory, attention, verbal fluency, and executive functions remains inconclusive (Delgado-Saborit et al., 2021; McLachlan et al., 2023; Petkus et al., 2020; Kulick et al., 2020).

In addition, there is a growing body of evidence on the possible protective effect of residential greenness on cognitive processes; however, the findings remain scarce and inconsistent, particularly among adults and older population (de Keijzer et al., 2016; Ricciardi et al., 2022). Greenness is thought to restore cognition by supporting beneficial behaviors such as physical activity and social inclusion, and by reducing psychological stress (Markevych et al., 2017). Furthermore, greenness is hypothesized to reduce exposure to air pollutants and noise (Delgado-Saborit et al., 2021; Wang et al., 2023a; Son et al., 2021).

Previous evidence suggested that neighborhood socioeconomic disadvantage (nSED) may increase the risk of poor cognitive function (Pase et al., 2022; Wu et al., 2015b). The characteristics of disadvantaged neighborhoods usually include a higher percentage of the unemployed population, a lower percentage of homeownership, higher household poverty, and lower safety and social cohesion (Pase et al., 2022; Zhang and Wu, 2017; Ross and Mirowsky, 2009; Rodrigues et al., 2021).

Importantly, environmental stressors and socioeconomic disadvantage are correlated; individuals with lower incomes are more prone to live in more disadvantaged areas with increased exposures to air pollution and noise, poor access to greenspace, and less walkable neighborhoods (Christensen et al., 2022; Cerin et al., 2023; Hajat et al., 2021). Such environmental and social barriers are increasingly recognized as barriers to physical activity and outdoor walking behaviors. According to previous systematic review and meta-analysis, physical activity was negatively associated with air pollution (An et al., 2018), suggesting that individuals living in highly exposed areas avoid physical activity, which undermines its beneficial effect on cognitive processes (Roberts et al., 2014). In addition, less walkable neighborhoods with higher distance to greenspace discourage individuals from engaging in physical activity (Ball et al., 2015; Jimenez et al., 2022).

Taking these findings into consideration, we hypothesize that the effects of neighborhood environment on cognitive functioning may be partly mediated by physical activity. To the best of our knowledge, the mediating role of physical activity has not been sufficiently investigated in previous studies. The aim of this study was to explore direct and indirect pathways of ambient air pollution, greenness and neighborhood socioeconomic deprivation on cognitive function and its domains using a structural equation modelling approach, with physical activity as potential mediator. Recognizing the potential interest differences in sex-specific patterns, we performed additional exploratory analyses by estimating models separately for men and women.

2. Methods

2.1. Study population

The study used data from the Czech arm of the HAPIEE (Health, Alcohol and Psychosocial Factors in Eastern Europe) cohort; the protocol and baseline characteristics have been reported previously (Peasey et al., 2006). In brief, the HAPIEE study is an ongoing prospective cohort study designed to examine the impact of socioeconomic and psychosocial conditions on non-communicable diseases in Central and Eastern European countries, namely Russia, Poland, the Czech Republic, and Lithuania. A random sample of men and women aged 45–69 at baseline (2002–2005) was selected from population registers. This study uses data from the Czech part of the study due to the availability of air pollution exposures. The Czech sub-cohort includes participants recruited in five cities (Hradec Králové, Liberec, Jihlava, Kroměříž and Ústí and Labem). For this study, we excluded participants living in two highly industrial areas to control for potential occupational bias. From an original sample of 7,301, only individuals who were surveyed by postal questionnaire at baseline and who underwent cognitive examination were included in the analysis (N = 4,178). The institutional ethics committees approved the study in all participating centers and the University College London. All participants provided informed consent.

2.2. Measures

2.2.1. Cognitive function

Three cognitive domains, namely verbal memory, verbal fluency, and processing speed, were tested during examination period (2003–2009) via three standard tests, including word recall, animal naming, and letter cancellation (Woodford and George, 2007a). First, a list of 10 words was recorded and played to participants over three consecutive and one delayed (at the end of the cognitive examination) 1-min trials. The word recall was measured using the average of correctly recalled words from these four trials (range 0–10). Second, the examinator asked the participant to name as many different animals as possible within 1 min. A total animal naming score was calculated as a sum of every correctly named animal. Third, the letter cancellation task instructed participants to cross out the letters “P” and “W” from a grid of randomly chosen letters as accurately as possible within 1 min (range 0–65). All three cognitive domains were assessed as continuous variables. The cognitive measures have been widely validated to detect expected changes in cognition in middle-aged and elderly populations (Woodford and George, 2007b; Wang et al., 2023b).

2.2.2. Air pollution exposure

Europe-wide land-use regression (LUR) model was used to estimate the annual average concentrations of $PM_{2.5}$ on 25-m resolution grid assigned to the participants’ residential addresses. The LUR model characteristics have been described in more detail elsewhere (Shen et al., 2022; de Hoogh et al., 2018). Briefly, the model was built using measured concentrations from routine monitoring stations across Europe. Potential predictors included satellite retrievals, chemical transport model estimates, and land-use variables. Supervised linear regression (SLR) was first used to select predictors, and then geographically weighted regression (GWR) estimated the spatially and annually varying coefficients. Multi-year models were developed using geographically and temporally weighted regression (GTWR) (Shen et al., 2022; de Hoogh et al., 2018). For this study, we used 4-year (2000–2003) average concentrations of $PM_{2.5}$ that were linked to participants’ residential addresses.

2.2.3. Greenness index

The greenness index was calculated from a tree canopy cover estimate based on Landsat data (Hansen et al., 1979). The tree canopy cover was defined as canopy closure percentage for each point on a raster grid for all vegetation taller than 5 m, in resolution approximately 30 × 30 m at the equator (Hansen et al., 1979). The index was assigned to participants' residential addresses and its neighborhood estimated as 30-min convex hull isochrones of pedestrian accessibility, using the "openrouteservice" R package built via Docker on OpenStreetMap network (Oleś, 2023). For each neighborhood polygon, mean values of extracted forest cover were calculated and used as an estimate of index of neighborhood greenness. The combination of tree canopy closure and pedestrian accessibility estimates aims to determine both tree density and viewshed greenness visibility.

2.2.4. Neighborhood socioeconomic deprivation

To assess the socioeconomic disadvantage of participants' neighborhoods, we used census-derived indices, including the percentage of the unemployed population, the percentage of the population with university education, and the percentage of the population with less than secondary education. The characteristics were measured at the lowest level of basic administrative units (neighborhoods) in 2001. In total, 171 neighborhoods covered participants' residential areas. Neighborhood socioeconomic deprivation (nSED) was derived from the indices using a principal component analysis. One extracted component was defined based on eigenvalues >1.0 (2.450) and explained 83.2% of the variance. Kaiser-Meyer-Olkin measure (0.609) and Bartlett's test of sphericity (<0.001) met the criteria for appropriateness of using factor analysis on our data. The oblimin rotation was applied as there was a reasonable assumption that the indices were correlated. Factor scores were assigned to all participants; higher factor scores indicated a higher level of neighborhood socioeconomic deprivation.

2.2.5. Physical activity

Physical activity was measured by the question "How many hours during a typical week do you engage in sports, games or hiking?". The variable was classified into four categories, including performing physical activity for less than 1 h/week, 1–3 h/week, 4–8 h/week, and 9 or more hours of physical activity/week.

2.2.6. Covariates

The covariates included in the model were selected based on a previous literature review of the potential predictors of cognitive aging in an elderly population. Age was coded as a continuous variable, while sex was assessed as a binary variable (men and women). Educational attainment was classified into four groups, including "incomplete primary or primary education", "vocational", "secondary", and "university". Marital status was grouped into two categories of "married/in partnership" and "single/divorced/widowed". Economic deprivation index was derived from three separate questions: "How often you do not have enough money for food for you & your family at present", "How often you do not have enough money for clothing you/your family at present" and "Do you have difficulty paying bills at present" that were measured on a Likert scale ranging from 0-never to 4-all the time. Deprivation index was calculated as the sum of all three items (range 0–12). More than half of the participants (51.9%) reported no financial deprivation, 25.1% reported 1–2 financial difficulties, and 23.0% reported ≥3 financial difficulties. Smoking status was classified into three categories, including "current smoker", "former smoker", and "nonsmoker". Alcohol frequency consumption was classified into five groups including "not drinking", "less than 1 day of drinking/month", "1–3 times/month", "4–8 times/month", and "9 or more days of drinking per month". Depressive symptoms were assessed using the Centre for Epidemiological Studies-Depression Scale, including 20 items asking the participants about their feelings during the last 7 days (e.g., "I felt sad"), rated from 0 = rarely/never to 3 = most/all of the time (Radloff, 1977). A total score was calculated as the sum of all items scored after reversing the positive mood items. The score ranged from 0 to the maximum of 60, with higher scores representing greater degrees of depressed mood. The presence of one of the selected chronic diseases (heart attack, ischemic heart disease, stroke, chronic respiratory disease, cancer, asthma) was coded as 0 = no and 1 = yes.

2.3. Statistical analysis

The descriptive characteristics of the sample were assessed. Categorical variables were described using frequencies, while continuous variables using means and standard deviations. Differences between groups were tested using Chi-Squared test and *t*-test. The Spearman correlation used to assess correlation between neighborhood characteristics. Statistical approaches were selected according to the research questions. First, we tested the individual effects of $PM_{2.5}$, greenness and nSED on memory, verbal fluency and concentration using linear regression. Model 1 was adjusted for age, while model 2 was adjusted for age, sex, education, marital status, individual deprivation, smoking, alcohol consumption, physical activity, chronic disease, and depression. Body mass index and diabetes were not included into the multivariate models because they did not alter the estimated effects. Second, we modeled mediation in structural equation modelling (SEM) to test the complex relationships between $PM_{2.5}$, greenness, nSED and cognition (Fig. 1). A latent variable named Global cognition was constructed from the three cognitive domains (verbal memory, verbal fluency, and processing speed). Direct, indirect and total effects of physical activity were tested, and mediation ratios were calculated by dividing indirect and total effects. Finally, exploratory analyses stratified by sex were conducted to examine potential sex-specific patterns in the associations. Due to the low intraclass correlation coefficients indicating minimal clustering of outcomes within neighborhoods (ICC = 7.6% for Global cognition), we opted for a standard regression approach rather than a multilevel design. Missing data were imputed using the full information maximum likelihood with robust standard errors (MLR).

All models reported standardized β coefficients, representing predicted change in the number of SD of outcomes (cognitive domains) for an increase of 1 SD in predictors (neighborhood characteristics). For all the tests, negative β indicates worse cognitive performance. Data analyses were performed using STATA software (version 16.0, StataCorp, College Station, TX, USA) and Mplus (version 8.6, Muthen & Muthen, CA, USA).

3. Results

3.1. Descriptive characteristics of the study population

The study population included 4,178 participants (55.6% women). The average age of the participants was 58.8 years. Most of the participants attained secondary education (41.7%) and were married or cohabited in partnership (75.6%). Chronic diseases were observed in 19.8% of the participants and were significantly more prevalent in men (25.0%) compared to women (15.7%, $p < 0.001$; Table S1). More than half of the individuals were former or current/occasional smokers and 42.4% of the participants consumed alcohol at least once a week. Additionally, men consumed alcohol more frequently compared to women ($p < 0.001$; Table S1). More than a quarter of the individuals (26.8%) performed physical activity less than 1 h/week. The four-year mean concentration of $PM_{2.5}$ was 24.5 μg/m^3 and the mean greenness index was 14.3%. The average neighborhood proportion of the unemployed population, the population with university education, and the population with less than secondary education (census-derived indices) was 8.5%, 11.3%, and 53.3%, respectively (Table 1). Weak but significant correlations were observed between neighborhood characteristics (e.g. for correlation between $PM_{2.5}$ and greenness: $r = -0.334$, $p < 0.001$; Table S2).

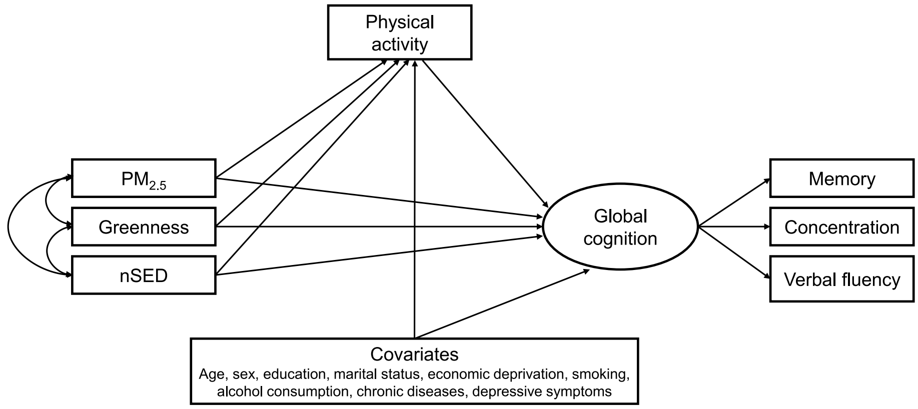

Fig. 1. Conceptual mediation structural equation model investigating the direct, indirect and total effects of neighborhood characteristics on global cognition.

Table 1
Descriptive characteristics of the study sample.

n	4,178
Age, mean (SD)	58.8 (7.06)
Sex, %	
Female	55.6
Male	44.4
Education, %	
Primary	9.5
Vocational	32.0
Secondary	41.7
University	16.9
Marital status, %	
Married/Cohabiting	75.6
Single/Divorced/Widowed	24.4
Chronic disease, %	
Yes	19.8
No	80.2
Smoking status, %	
Never	47.0
Former	29.6
Current or occasional	23.4
Physical activity, %	
<1 h/week	26.8
1–3 h/week	26.2
4–8 h/week	28.2
≥9 h/week	18.8
Alcohol frequency, %	
Never	10.6
<1/month	25.9
1-3/month	21.1
1-4/week	28.9
≥5/week	13.5
Depression score, mean (SD)	9.9 (8.21)
Deprivation index, mean (SD)	1.5 (2.18)
No deprivation (0), %	51.9
Low level of deprivation (1–2), %	25.1
High level of deprivation (≥3), %	23.0
Cognitive functions, mean (SD)	
Verbal memory	7.9 (1.20)
Verbal fluency	24.2 (6.38)
Processing speed	18.5 (4.56)
Environmental exposures	
$PM_{2.5}$, [μg/m^3], mean (SD)	24.5 (2.79)
Greenness index [%], mean (SD)	14.3 (9.90)
Neighborhood SED, mean (SD)	
% unemployed population	8.5 (4.03)
% of population with university education	11.3 (3.76)
% of population with less than secondary education	53.3 (7.09)

3.2. The associations between air pollution, greenness, nSED and cognitive domains

Age-adjusted as well as fully-adjusted models revealed significant negative associations between $PM_{2.5}$ and worse memory (fully adjusted β = −0.108; 95%CI: 0.133 to −0.083), concentration (fully adjusted β = −0.044; 95%CI: 0.071 to −0.017) and global cognition (fully adjusted β = −0.074; 95%CI: 0.107 to −0.041; Table 2). In contrast, increased exposure to greenness was positively associated with better memory performance (fully adjusted β = 0.050; 95%CI: 0.025 to 0.074) and global cognition (fully adjusted β = 0.038; 95%CI: 0.006 to 0.070). No significant associations were found between air pollution or greenness exposures and verbal fluency in either age-adjusted or fully-adjusted models. Finally, higher neighborhood socioeconomic deprivation was inversely associated with all cognitive domains (e.g., for memory: β = −0.115; 95%CI: 0.141 to −0.090). Sex-specific analyses showed robust associations between environmental characteristics and memory and global cognition, but findings for verbal fluency and concentration domains were less consistent, possibly because of smaller sample size. For instance, increased exposures to $PM_{2.5}$ and greenness predicted a lower, respectively higher concentration performance in men, but not in women. (Table S3). However, the interactions with sex were not statistically significant.

3.3. The mediation effect by physical activity in the associations between air pollution, greenness, nSED and global cognition

The results of mediation structural equation modelling are presented in Table 3. Observed direct, indirect, and total effects, together with mediation ratios, are shown in Table 4. A satisfactory model fit was achieved: χ^2 (105) = 8414.2, $p < 0.001$, CFI = 0.980, RMSEA = 0.031, 90% CI RMSEA (0.027, 0.035), Table 3), and the latent variable of global cognition was adequately loaded by the cognitive domains (Fig. S1).

Increased $PM_{2.5}$ exposure (β = −0.043; 95%CI: 0.071 to −0.016) and nSED (β = −0.044; 95%CI: 0.072 to −0.016) were negatively associated with lower physical activity, while no evidence was observed for the higher exposure to greenness. Lower global cognition was significantly predicted by all neighborhood characteristics (e.g. for nSED: β = −0.147; 95%CI: 0.182 to −0.115). Additionally, higher physical activity predicted better global cognitive function (β = 0.133; 95%CI: 0.099 to 0.167; Table 3). In model stratified by sex, increased $PM_{2.5}$ exposure was linked with lower physical activity in women (β = −0.046; 95%CI: 0.084 to −0.008), but not in men; as the confidence intervals in men and women overlapped, the differences were not statistically significant (Table S4).

The SEM model revealed a significant mediating role of physical activity in the associations between $PM_{2.5}$ exposure (β = −0.006; 95%CI: 0.010 to −0.002) and nSED (β = −0.006; 95%CI: 0.010 to −0.002) in global cognitive function (Table 4). The total mediation ratios ranged from 3.9% to 6.5% in nSED and $PM_{2.5}$, respectively. No mediating role of physical activity was observed in the association between greenness and global cognition (Table 4). In models stratified by sex, the results revealed a significant indirect effect through physical activity in the

Table 2
The individual effects of $PM_{2.5}$, greenness and nSED on cognitive domains.

		Memory		Verbal fluency		Concentration		Global cognition	
		β	95% CI	β	95% CI	β	95% CI	β	95% CI
$PM_{2.5}$	Model 1	**−0.104**	**−0.130 to -0.077**	0.012	−0.015 to 0.039	**−0.038**	**−0.061 to -0.011**	**−0.079**	**−0.112 to -0.046**
	Model 2	**−0.108**	**−0.133 to -0.083**	−0.004	−0.030 to 0.022	**−0.044**	**−0.071 to -0.017**	**−0.074**	**−0.107 to -0.041**
Greenness	Model 1	**0.047**	**0.021 to 0.073**	−0.007	−0.033 to 0.019	0.019	−0.008 to 0.045	0.029	−0.003 to 0.060
	Model 2	**0.050**	**0.025 to 0.074**	0.003	−0.022 to 0.028	0.020	−0.007 to 0.046	**0.038**	**0.006 to 0.070**
nSED	Model 1	**−0.163**	**−0.190 to -0.137**	**−0.099**	**−0.126 to -0.072**	**−0.070**	**−0.097 to -0.042**	**−0.202**	**−0.234 to -0.170**
	Model 2	**−0.115**	**−0.141 to -0.090**	**−0.039**	**−0.066 to -0.013**	**−0.035**	**−0.063 to -0.008**	**−0.122**	**−0.155 to -0.088**

Model 1 adjusted for age. Model 2 adjusted for age, sex, education, marital status, individual deprivation, smoking, alcohol consumption, physical activity, chronic disease, and depression. Standardized β coefficients represent predicted change in the number of SD of outcomes for an increase of 1 SD in predictors.

Table 3
Estimated associations between variables in the mediation structural equation model.

Predictor	Outcome	β	95% CI
$PM_{2.5}$	→ Physical activity	**−0.043**	**−0.071 to -0.016**
	→ Global cognition	**−0.087**	**−0.122 to -0.052**
Greenness	→ Physical activity	0.015	−0.012 to 0.043
	→ Global cognition	**0.036**	**0.001 to 0.069**
nSED	→ Physical activity	**−0.044**	**−0.072 to -0.016**
	→ Global cognition	**−0.147**	**−0.182 to -0.115**
Physical activity	→ Global cognition	**0.133**	**0.099 to 0.167**

Model fit: $\chi^2(105) = 8414.2$, $p < 0.001$, CFI = 0.980, RMSEA = 0.031, 90% CI RMSEA (0.027, 0.035). Model adjusted for age, sex, education, marital status, individual deprivation, smoking, alcohol consumption, physical activity, chronic disease, and depression. Standardized β coefficients represent predicted change in the number of SD of outcomes for an increase of 1 SD in predictors.

association between $PM_{2.5}$ and global cognition in women (β = −0.006; 95%CI: 0.012 to −0.001) but not in men. Finally, the results showed a significant indirect effect through physical activity in the association between nSED and global cognition in men (β = −0.006; 95%CI: 0.012 to −0.001) but not in women (Table S5).

4. Discussion

In this study of 4,178 middle-aged and older individuals from the Czech Republic, we aimed to investigate the direct effects of neighborhood characteristics, including ambient air pollution, greenness and neighborhood socioeconomic deprivation, on cognitive function and its specific domains. In our data, all these variables showed association with cognition in the predicted directions. In addition, we found a mediating effect of physical activity in the associations between neighborhood characteristics and global cognition which appeared stronger in women than in men.

We observed a significant negative association between $PM_{2.5}$ exposure and cognitive function that is in line with previous studies and meta-analysis performed in different aging populations. A systematic review and meta-analysis conducted by McLachlan et al., in 2023 including 26 studies reported an increased risk of $PM_{2.5}$ exposures on general cognitive function. Similarly, a systematic review published by Zhao et al., in 2021 suggested that higher exposure to $PM_{2.5}$ predicted an elevated risk of a faster decline of cognitive functions. The detrimental effect of long-term exposure to $PM_{2.5}$ on cognition was supported by several potential pathways. It has been well documented that air pollutants alter cognitive functions primarily via oxidative stress and systematic and neuronal inflammation (Lee et al., 2023; Calderón-Garcidueñas et al., 2015). Recent studies additionally suggested that disruption of the homeostasis of the gut microbiome caused by fine particle exposure can induce neuroinflammation and neurodegeneration (Lee et al., 2023; Panda et al., 2023). Additionally, neuro-imaging studies also reported associations between air pollutant exposures and grey matter volume reduction (de Prado Bert et al., 2018).

Previous studies reported the inconsistency regarding the effects of ambient air pollution on domain-specific cognitive performance. For instance, the studies conducted by Petkus et al., in 2020 (Petkus et al., 2020), and Kulick et al., in 2020 (Kulick et al., 2020) reported a negative significant association between $PM_{2.5}$ exposures and memory, although studies performed by Schikowski et al., in 2015 (Schikowski et al., 2015), Gatto et al., in 2014 (Gatto et al., 2014) and Wang et al., in 2020 (Wang et al., 2023a) found no significant associations. Similarly, the associations between air pollutants and verbal fluency and concentration remained inconsistent across studies (Delgado-Saborit et al., 2021; Kulick et al., 2020; Gatto et al., 2014). In the present study, we found a negative significant association between $PM_{2.5}$ and memory, while no statistically significant effect of $PM_{2.5}$ exposure on verbal fluency was found. However, our study was not well suited to elucidate the potential underlying biological pathways and mechanisms through which air pollution may affect specific cognitive domains. Existing evidence suggest that certain brain regions (e.g. hippocampus, local atrophy of the frontoparietal network) may be more susceptible to air pollutants or greenness exposures that may partially explain the variability in effect sizes across cognitive domains (Nußbaum et al., 2020). The findings from sex-stratified analyses showed that $PM_{2.5}$ was negatively associated with concentration in males but not in females. This result is in contrast with a previous study reporting significantly greater vulnerability to air pollution in women compared to men (Mo et al., 2023). The discrepancy may be explained by exposure misclassification related to occupational exposures and other risk factors.

In addition, our results showed a protective effect of residential

Table 4
Standardized direct, indirect, and total effects of mediation structural equation model for prediction of global cognition.

	Direct effect		Indirect effect		Total effect		Mediation ratio
	β	95% CI	β	95% CI	β	95% CI	%
$PM_{2.5}$	**−0.087**	**−0.122 to -0.052**	**−0.006**	**−0.010 to -0.002**	**−0.092**	**−0.127 to -0.058**	**6.5**
Greenness	**0.036**	**0.001 to 0.069**	0.002	−0.001 to 0.006	**0.038**	**0.004 to 0.071**	5.3
nSED	**−0.147**	**−0.182 to -0.115**	**−0.006**	**−0.010 to -0.002**	**−0.153**	**−0.188 to -0.120**	**3.9**

Model adjusted for age, sex, education, marital status, individual deprivation, smoking, alcohol consumption, physical activity, chronic disease, and depression. Standardized β coefficients represent predicted change in the number of SD of outcomes for an increase of 1 SD in predictors.

greenness on cognitive functions. The most pronounced cognitive domains associated with greenness included memory and concentration in the subgroup of males. According to a recently published systematic review of Ricciardi et al., in 2022 (Ricciardi et al., 2022), the evidence for the protective effect of greenspace exposure on cognitive functions is suggestive but inconsistent, especially among adults and older people (de Keijzer et al., 2016; Ricciardi et al., 2022). Despite the discrepancies in the epidemiological conclusions, numerous underlying mechanisms explaining the beneficial effect of greenness on cognition have been proposed. Greenness is thought to reduce a broad range of adverse health impacts, including neurodegenerative disorders (Zhao et al., 2021b; Rodriguez-Loureiro et al., 2022), and is assumed to preserve cognition by encouraging beneficial behaviors such as social cohesion, reducing psychological stress, and mitigating environmental hazards, including noise or air pollution (Markevych et al., 2017).

Furthermore, our findings suggested that individuals living in more disadvantageous neighborhoods were more prone to experience worse cognitive performance, including memory. Effects of nSED on verbal fluency and concentrations were less pronounced and inconsistent among the sexes. Neighborhood socioeconomic deprivation has been previously reported for harmful effects on cognition in the elderly (Steptoe and Zaninotto, 2020). For instance, the study conducted by Pase et al., in 2022 suggested that living in the lowest 20% of the most disadvantaged neighborhoods was associated with impaired cognition, including memory (Pase et al., 2022). Similar findings were reported also in studies conducted by Christensen et al., in 2022 (Christensen et al., 2022), and Li et al., in 2022 (Li et al., 2022). Numerous mechanisms may play a role in the effect of nSED on cognitive health, including access to health care facilities and leisure centers; distance to greenspace and general walkability; perception of safety; and higher exposures to ambient air pollution and noise (Christensen et al., 2022; Cerin et al., 2023; Hajat et al., 2021). Furthermore, chronic stress that accumulates over the course of a person's life may lead to early deterioration of biological systems (Avila-Rieger et al., 2022). For example, socioeconomically disadvantaged individuals were found to experience accelerated biological aging and increased genetic methylation (Dalecka et al., 2024; Shen et al., 2023).

Our study confirmed a significant protective effect of physical activity on cognitive functions that was reported in previous studies (Livingston et al., 2020; Veronese et al., 2023; Erickson et al., 2019). Growing evidence suggests an important role of the neurotrophin brain-derived neurotrophic factor (BNDF) in the mechanism through which physical activity enhances brain plasticity and improves cognition (Bos et al., 2014). Importantly, our study revealed a weak but significant mediating role of physical activity in the associations of $PM_{2.5}$ exposures and nSED on global cognitive function. These results suggest that those living in areas with higher air pollution exposures and socioeconomic deprivation are more likely to be physically inactive, which undermines its beneficial effect on cognition processes. Previous research showed that physical activity can induce cognitive benefits even increased air pollution exposures (Liu et al., 2023). Our sex-stratified analysis showed a larger mediating effect of physical activity in women than in men. Although the study did not have statistical power to detect interactions, such findings align with previous studies reporting larger effect sizes between physical activity and cognition in women (Barha et al., 2017). The study conducted by Roberts et al., in 2014 (Roberts et al., 2014) on U.S. population proposed that the significant association between physical inactivity and ambient air pollution may be explained by physiological effects such as difficulty breathing; and psychosocial effects including smog appearance disincentivizing physical activity, together with higher awareness of the health risk linked to air pollution. Similarly, a number of nSED characteristics, including increased criminality, lower perception of safety, poor walkability and greater distances to greenness, have been considered as risk factors of physical inactivity (Christensen et al., 2022; Cerin et al., 2023; Hajat et al., 2021). We hypothesized that higher exposure to greenness may be associated with better cognitive performance through increased opportunities for physical activity; however, no mediating effect was observed in our study. These findings align with the study conducted by de Keizer et al., in 2018 on the English population that revealed a significant direct effect of residential greenness on cognitive performance but not indirectly through physical activity (de Keijzer et al., 2018). In addition, a mediating effect of physical activity was not found in other study conducted by Zijlema et al., in 2017 (Zijlema et al., 2017) using several European cohorts. The mediating role of physical activity was statistically significant, but of modest magnitude, suggesting that other mechanisms play a role in the association between neighborhood characteristics and cognition in middle-aged and older individuals. For instance, the association between neighborhood socioeconomic deprivation and cognitive health may be partially explained by worse access to healthcare and poor social engagement within individuals living in highly deprived neighborhoods as shown previously (Butler et al., 2013). Unfortunately, we did not have the data to assess these characteristics.

4.1. Strengths and limitations

The HAPIEE study is a well-established prospective cohort recruited from a representative sample of older individuals living in the Czech Republic. To the best of our knowledge, this is the first study on this topic conducted in Eastern Europe, providing important insights and evidence from this region. The major strength of this study is that it estimates the complex relationships between neighborhood environment, physical activity, and cognitive performance in older adults, which reveals important interplay mechanisms. In addition, we accounted for multiple potential covariates to better control for residual confounding including healthy behaviors, physical health, mental health and socioeconomic deprivation. Finally, we estimated greenness exposure based on the combination of tree canopy closure and pedestrian accessibility that better reflected the representation of regularly accessed areas.

Several limitations of this study need to be acknowledged. First, our study depended on outcomes measured at a short time point, which did not allow us to examine causal associations or temporality of associations. However, the Czech Republic has much lower residential mobility than western European countries, and reverse causality was at least partly controlled by examining the neighborhood environment prior to cognitive outcomes. The study participants live mostly in urban areas which introduced difficulties in generalization of our results. Furthermore, the participants living in highly industrialized areas were excluded from the study sample as additional occupational exposures might cause bias. The participants in the study sample were generally more educated, exposed to significantly lower concentrations to $PM_{2.5}$ and lived in less deprived neighborhoods, resulting in better cognitive performance on average. The age and sex distribution of the included and excluded participants was comparable.

The second, and related, limitation is that we were unable to capture lifetime environmental exposures. However, our air pollution estimates may reflect some extent of long-term exposures as it refers to a four-year average of exposures. Also, it is hypothesized that air pollution concentrations are highly correlated over time. Even though most of the HAPIEE respondents reported living in the same address between the first and the follow-up examinations (2002–2010), possible exposure misclassification might occur due to participants moving prior to their enrollment to the HAPIEE. This limitation has also been reported in previous studies (Christensen et al., 2022; Li et al., 2022); therefore, future investigations should account for the residential mobility of the participants.

Third, only three indicators were employed to create the nSED composite measure that corresponded with education and employment domains of socioeconomic status. Previous studies utilized socioeconomic domains including poverty/income (e.g., percent households in poverty, percent female-headed households with dependent children, etc.), occupation (e.g., percent males and females not in management, business, science, and arts occupations, etc.) and housing properties (e.g., percent crowded households, etc.) that were widely used in research of nSED and health (Christensen et al., 2022; Li et al., 2022). As none of these indicators were available from the Czech census data, nSED may not accurately reflect all residential social, economic, and cultural aspects.

Fourth, physical activity was measured using a single question that did not take into account intensity (moderate, vigorous), type (aerobic, muscle-strengthening), specification (individual vs team sports) and the seasonality of performed sport activities.

Finally, a reverse association between physical activity and cognitive functioning might occur as the previous evidence indicated that cognitive decline may result in decreased physical activity as individuals experience difficulties with mobility, coordination, and overall motivation (O'Donovan et al., 2022). However, such a reverse association is more likely to occur in individuals with severe cognitive impairment or dementia, rather than mild cognitive decline that was typical for our study participants.

5. Conclusion

This cross-sectional study found that older participants living in air-polluted or socially disadvantaged neighborhoods had impaired cognitive functions. In contrast, higher exposure to greenness was found to have a beneficial impact on cognitive performance. This study provided evidence that disadvantaged neighborhoods led to lower physical activity, which resulted in worse cognitive health in older adults. Thus, urban planning may need to consider such obstacles and provide opportunities for promoting healthy behaviors among at-risk groups. Additionally, public health and social policies need to ensure that the challenges related to living in such areas are addressed to encourage equality in healthy aging.

CRediT authorship contribution statement

A. Dalecká: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **A. Kšiňan:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis. **D. Szabó:** Writing – review & editing, Methodology. **N. Čapková:** Writing – review & editing, Data curation. **H. Pikhart:** Writing – review & editing, Supervision, Methodology, Conceptualization. **M. Bobák:** Writing – review & editing, Supervision, Funding acquisition, Data curation, Conceptualization.

Acknowledgement

This work was supported from the European Union's Horizon 2020 research and innovation programme under grant agreement No 857487 (R-Exposome Chair), No 857560 (CETOCOEN Excellence), and No 874627 (EXPANSE). This publication reflects only the author's view, and the European Commission is not responsible for any use that may be made of the information it contains. Authors thank the RECETOX Research Infrastructure (No LM2023069) financed by the Ministry of Education, Youth and Sports, and the Operational Programme Research, Development and Education (the CETOCOEN EXCELLENCE project No. CZ.02.1.01/0.0/0.0/17_043/0009632) for supportive background. This output was supported by the NPO „Systemic Risk Institute", number LX22NPO5101, funded by European Union – Next Generation EU (Ministry of Education, Youth and Sports, NPO: EXCELES). The HAPIEE study was funded by the Welcome Trust (064947 and 081081), the US National Institute on Aging (R01 AG23522-01), and a grant from MacArthur Foundation.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijheh.2025.114521.

References

Aly, M., Kojima, H., 2020. Acute moderate-intensity exercise generally enhances neural resources related to perceptual and cognitive processes: a randomized controlled ERP study. Ment Health Phys Act 19, 100363. https://doi.org/10.1016/j.mhpa.2020.100363.

An, R., Zhang, S., Ji, M., Guan, C., 2018. Impact of ambient air pollution on physical activity among adults: a systematic review and meta-analysis. Perspect Public Health 138, 111–121. https://doi.org/10.1177/1757913917726567.

Avila-Rieger, J., Turney, I.C., Vonk, J.M.J., Esie, P., Seblova, D., Weir, V.R., et al., 2022. Socioeconomic status, biological aging, and memory in a diverse national sample of older US men and women. Neurology. https://doi.org/10.1212/WNL.0000000000201032, 10.1212/WNL.0000000000201032.

Ball, K., Carver, A., Downing, K., Jackson, M., O'Rourke, K., 2015. Addressing the social determinants of inequities in physical activity and sedentary behaviours. Health Promot. Int. 30, ii8–19. https://doi.org/10.1093/heapro/dav022.

Barha, C.K., Davis, J.C., Falck, R.S., Nagamatsu, L.S., Liu-Ambrose, T., 2017. Sex differences in exercise efficacy to improve cognition: a systematic review and meta-analysis of randomized controlled trials in older humans. Front. Neuroendocrinol. 46, 71–85. https://doi.org/10.1016/j.yfrne.2017.04.002.

Bos, I., De Boever, P., Int Panis, L., Meeusen, R., 2014. Physical activity, air pollution and the brain. Sports Med. 44, 1505–1518. https://doi.org/10.1007/s40279-014-0222-6.

Butler, D.C., Petterson, S., Phillips, R.L., Bazemore, A.W., 2013. Measures of social deprivation that predict health care access and need within a rational area of primary care service delivery. Health Serv. Res. 48, 539–559. https://doi.org/10.1111/j.1475-6773.2012.01449.x.

Calderón-Garcidueñas, L., Calderón-Garcidueñas, A., Torres-Jardón, R., Avila-Ramírez, J., Kulesza, R.J., Angiulli, A.D., 2015. Air pollution and your brain: what do you need to know right now. Prim. Health Care Res. Dev. 16, 329–345. https://doi.org/10.1017/S146342361400036X.

Campbell, N.L., Unverzagt, F., LaMantia, M.A., Khan, B.A., Boustani, M.A., 2013. Risk factors for the progression of mild cognitive impairment to dementia. Clin. Geriatr. Med. 29, 873. https://doi.org/10.1016/J.CGER.2013.07.009.

Cerin, E., Barnett, A., Wu, Y.-T., Martino, E., Shaw, J.E., Knibbs, L.D., et al., 2023. Do neighbourhood traffic-related air pollution and socio-economic status moderate the associations of the neighbourhood physical environment with cognitive function? Findings from the AusDiab study. Sci. Total Environ. 858, 160028. https://doi.org/10.1016/j.scitotenv.2022.160028.

Cheng, W., Zhang, Z., Cheng, W., Yang, C., Diao, L., Liu, W., 2018. Associations of leisure-time physical activity with cardiovascular mortality: a systematic review and meta-analysis of 44 prospective cohort studies. Eur J Prev Cardiol 25, 1864–1872. https://doi.org/10.1177/2047487318795194.

Christensen, G.M., Li, Z., Pearce, J., Marcus, M., Lah, J.J., Waller, L.A., et al., 2022. The complex relationship of air pollution and neighborhood socioeconomic status and their association with cognitive decline. Environ. Int. 167, 107416. https://doi.org/10.1016/j.envint.2022.107416.

Clare, L., Wu, Y.T., Teale, J.C., MacLeod, C., Matthews, F., Brayne, C., et al., 2017. Potentially modifiable lifestyle factors, cognitive reserve, and cognitive function in later life: a cross-sectional study. PLoS Med. 14, 1–14. https://doi.org/10.1371/journal.pmed.1002259.

Dalecka, A., Bartoskova Polcrova, A., Pikhart, H., Bobak, M., Ksinan, A.J., 2024. Living in poverty and accelerated biological aging: evidence from population-representative sample of U.S. adults. BMC Publ. Health 24, 458. https://doi.org/10.1186/s12889-024-17960-w.

Delgado-Saborit, J.M., Guercio, V., Gowers, A.M., Shaddick, G., Fox, N.C., Love, S., 2021. A critical review of the epidemiological evidence of effects of air pollution on dementia, cognitive function and cognitive decline in adult population. Sci. Total Environ. 757, 143734. https://doi.org/10.1016/j.scitotenv.2020.143734.

Erickson, K.I., Hillman, C., Stillman, C.M., Ballard, R.M., Bloodgood, B., Conroy, D.E., et al., 2019. Physical activity, cognition, and brain outcomes: a review of the 2018 physical activity guidelines. Med. Sci. Sports Exerc. 51, 1242–1251. https://doi.org/10.1249/MSS.0000000000001936.

European Environmental Agency, 2022. Air Quality in Europe 2022.

Fabbri, E., An, Y., Zoli, M., Tanaka, T., Simonsick, E.M., Kitner-Triolo, M.H., et al., 2016. Association between accelerated multimorbidity and age-related cognitive decline in older Baltimore longitudinal study of aging participants without dementia. J. Am. Geriatr. Soc. 64, 965–972. https://doi.org/10.1111/jgs.14092.

Gatto, N.M., Henderson, V.W., Hodis, H.N., John, J.A., Lurmann, F., Chen, J.-C., et al., 2014. Components of air pollution and cognitive function in middle-aged and older adults in Los Angeles. Neurotoxicology 40, 1–7. https://doi.org/10.1016/j.neuro.2013.09.004.

Hajat, A., MacLehose, R.F., Rosofsky, A., Walker, K.D., Clougherty, J.E., 2021. Confounding by socioeconomic status in epidemiological studies of air pollution and health: challenges and opportunities. Environ. Health Perspect. 129. https://doi.org/10.1289/EHP7980.

Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., et al., 1979. High-resolution global maps of 21st-century forest cover change. Science 342, 850–853. https://doi.org/10.1126/science.1244693, 2013.

Hillman, C.H., Erickson, K.I., Kramer, A.F., 2008. Be smart, exercise your heart: exercise effects on brain and cognition. Nat. Rev. Neurosci. 9, 58–65. https://doi.org/10.1038/nrn2298.

de Hoogh, K., Chen, J., Gulliver, J., Hoffmann, B., Hertel, O., Ketzel, M., et al., 2018. Spatial PM2.5, NO2, O3 and BC models for western Europe – evaluation of spatiotemporal stability. Environ. Int. 120, 81–92. https://doi.org/10.1016/j.envint.2018.07.036.

Hüls, A., Vierkötter, A., Sugiri, D., Abramson, M.J., Ranft, U., Krämer, U., et al., 2018. The role of air pollution and lung function in cognitive impairment. Eur. Respir. J. 51, 1701963. https://doi.org/10.1183/13993003.01963-2017.

Iso-Markku, P., Aaltonen, S., Kujala, U.M., Halme, H.-L., Phipps, D., Knittle, K., et al., 2024. Physical activity and cognitive decline among older adults. JAMA Netw. Open 7, e2354285. https://doi.org/10.1001/jamanetworkopen.2023.54285.

Jimenez, M.P., Elliott, E.G., DeVille, N.V., Laden, F., Hart, J.E., Weuve, J., et al., 2022. Residential green space and cognitive function in a large cohort of middle-aged women. JAMA Netw. Open 5, e229306. https://doi.org/10.1001/jamanetworkopen.2022.9306.

de Keijzer, C., Gascon, M., Nieuwenhuijsen, M.J., Dadvand, P., 2016. Long-term green space exposure and cognition across the life course: a systematic review. Curr Environ Health Rep 3, 468–477. https://doi.org/10.1007/s40572-016-0116-x.

de Keijzer, C., Tonne, C., Basagaña, X., Valentín, A., Singh-Manoux, A., Alonso, J., et al., 2018. Residential surrounding greenness and cognitive decline: a 10-year follow-up of the whitehall II cohort. Environ. Health Perspect. 126. https://doi.org/10.1289/EHP2875.

Kulick, E.R., Elkind, M.S.V., Boehme, A.K., Joyce, N.R., Schupf, N., Kaufman, J.D., et al., 2020. Long-term exposure to ambient air pollution, APOE-ε4 status, and cognitive decline in a cohort of older adults in northern Manhattan. Environ. Int. 136, 105440. https://doi.org/10.1016/j.envint.2019.105440.

Lee, J., Weerasinghe-Mudiyanselage, P.D.E., Kim, B., Kang, S., Kim, J.-S., Moon, C., 2023. Particulate matter exposure and neurodegenerative diseases: a comprehensive update on toxicity and mechanisms. Ecotoxicol. Environ. Saf. 266, 115565. https://doi.org/10.1016/j.ecoenv.2023.115565.

Lees, C., Hopkins, J., 2013. Effect of aerobic exercise on cognition, academic achievement, and psychosocial function in children: a systematic review of randomized control trials. Prev. Chronic Dis. 10, 130010. https://doi.org/10.5888/pcd10.130010.

Li, Z., Christensen, G.M., Lah, J.J., Marcus, M., Russell, A.G., Ebelt, S., et al., 2022. Neighborhood characteristics as confounders and effect modifiers for the association between air pollution exposure and subjective cognitive functioning. Environ. Res. 212, 113221. https://doi.org/10.1016/j.envres.2022.113221.

Liegro, Di, Schiera, Proia, Liegro, Di, 2019. Physical activity and brain health. Genes 10, 720. https://doi.org/10.3390/genes10090720.

Lista, I., Sorrentino, G., 2010. Biological mechanisms of physical activity in preventing cognitive decline. Cell. Mol. Neurobiol. 30, 493–503. https://doi.org/10.1007/s10571-009-9488-x.

Liu, J., Liu, R., Zhang, Y., Lao, X., Mandeville, K.L., Ma, X., et al., 2023. Leisure-time physical activity mitigated the cognitive effect of PM2.5 and PM2.5 components exposure: evidence from a nationwide longitudinal study. Environ. Int. 179, 108143. https://doi.org/10.1016/j.envint.2023.108143.

Livingston, G., Huntley, J., Sommerlad, A., Ames, D., Ballard, C., Banerjee, S., et al., 2020. Dementia prevention, intervention, and care: 2020 report of the Lancet Commission. Lancet 396, 413–446. https://doi.org/10.1016/S0140-6736(20)30367-6.

Ma, C.-L., Ma, X.-T., Wang, J.-J., Liu, H., Chen, Y.-F., Yang, Y., 2017. Physical exercise induces hippocampal neurogenesis and prevents cognitive decline. Behav. Brain Res. 317, 332–339. https://doi.org/10.1016/j.bbr.2016.09.067.

Markevych, I., Schoierer, J., Hartig, T., Chudnovsky, A., Hystad, P., Dzhambov, A.M., et al., 2017. Exploring pathways linking greenspace to health: theoretical and methodological guidance. Environ. Res. 158, 301–317. https://doi.org/10.1016/j.envres.2017.06.028.

McLachlan, J., Cox, S.R., Pearce, J., Valdés Hernández, M., del, C., 2023. Long-term exposure to air pollution and cognitive function in older adults: a systematic review and meta-analysis. Front. Environ. Health 2. https://doi.org/10.3389/fenvh.2023.1205443.

Mo, S., Wang, Y., Peng, M., Wang, Q., Zheng, H., Zhan, Y., et al., 2023. Sex disparity in cognitive aging related to later-life exposure to ambient air pollution. Sci. Total Environ. 886, 163980. https://doi.org/10.1016/j.scitotenv.2023.163980.

Niederer, I., Kriemler, S., Gut, J., Hartmann, T., Schindler, C., Barral, J., et al., 2011. Relationship of aerobic fitness and motor skills with memory and attention in preschoolers (Ballabeina): a cross-sectional and longitudinal study. BMC Pediatr. 11, 34. https://doi.org/10.1186/1471-2431-11-34.

Nußbaum, R., Lucht, S., Jockwitz, C., Moebus, S., Engel, M., Jöckel, K.-H., et al., 2020. Associations of air pollution and noise with local brain structure in a cohort of older adults. Environ. Health Perspect. 128. https://doi.org/10.1289/EHP5859.

Oleś, A., 2023. Openrouteservice: Openrouteservice API Client.

O'Donovan, G., Lee, I.-M., Hamer, M., García-Garro, P., Duran-Aniotz, C., Ibáñez, A., et al., 2022. The burden of mild cognitive impairment attributable to physical inactivity in Colombia. European Review of Aging and Physical Activity 19, 28. https://doi.org/10.1186/s11556-022-00307-y.

Panda, S.R., Chaudhari, V.B., Ahmed, S., Kwatra, M., Jala, A., Ponneganti, S., et al., 2023. Ambient particulate matter (PM2.5) exposure contributes to neurodegeneration through the microbiome-gut-brain axis: therapeutic role of melatonin. Environ. Toxicol. Pharmacol. 101, 104183. https://doi.org/10.1016/j.etap.2023.104183.

Pase, M.P., Rowsthorn, E., Cavuoto, M.G., Lavale, A., Yassi, N., Maruff, P., et al., 2022. Association of neighborhood-level socioeconomic measures with cognition and dementia risk in Australian adults. JAMA Netw. Open 5, e224071. https://doi.org/10.1001/jamanetworkopen.2022.4071.

Pearce, M., Garcia, L., Abbas, A., Strain, T., Schuch, F.B., Golubic, R., et al., 2022. Association between physical activity and risk of depression. JAMA Psychiatr. 79, 550. https://doi.org/10.1001/jamapsychiatry.2022.0609.

Peasey, A., Bobak, M., Kubinova, R., Malyutina, S., Pajak, A., Tamosiunas, A., et al., 2006. Determinants of cardiovascular disease and other non-communicable diseases in Central and Eastern Europe: rationale and design of the HAPIEE study. BMC Publ. Health 6, 255. https://doi.org/10.1186/1471-2458-6-255.

Petkus, A.J., Younan, D., Widaman, K., Gatz, M., Manson, J.E., Wang, X., et al., 2020. Exposure to fine particulate matter and temporal dynamics of episodic memory and depressive symptoms in older women. Environ. Int. 135, 105196. https://doi.org/10.1016/j.envint.2019.105196.

de Prado Bert, P., Mercader, E.M.H., Pujol, J., Sunyer, J., Mortamais, M., 2018. The effects of air pollution on the brain: a review of studies interfacing environmental epidemiology and neuroimaging. Curr Environ Health Rep 5, 351–364. https://doi.org/10.1007/s40572-018-0209-9.

Przedborski, S., Vila, M., Jackson-Lewis, V., 2003. Series Introduction: neurodegeneration: what is it and where are we? J. Clin. Invest. 111, 3–10. https://doi.org/10.1172/JCI17522.

Radloff, L.S., 1977. The CES-D scale. Appl. Psychol. Meas. 1, 385–401. https://doi.org/10.1177/014662167700100306.

Ricciardi, E., Spano, G., Lopez, A., Tinella, L., Clemente, C., Elia, G., et al., 2022. Long-term exposure to greenspace and cognitive function during the lifespan: a systematic review. Int. J. Environ. Res. Publ. Health 19, 11700. https://doi.org/10.3390/ijerph191811700.

Roberts, J.D., Voss, J.D., Knight, B., 2014. The association of ambient air pollution and physical inactivity in the United States. PLoS One 9, e90143. https://doi.org/10.1371/journal.pone.0090143.

Rodrigues, D.E., César, C.C., Xavier, C.C., Caiaffa, W.T., Proietti, F.A., 2021. Exploring neighborhood socioeconomic disparity in self-rated health: a multiple mediation analysis. Prev. Med. 145, 106443. https://doi.org/10.1016/j.ypmed.2021.106443.

Rodriguez-Loureiro, L., Gadeyne, S., Bauwelinck, M., Lefebvre, W., Vanpoucke, C., Casas, L., 2022. Long-term exposure to residential greenness and neurodegenerative disease mortality among older adults: a 13-year follow-up cohort study. Environ. Health 21, 49. https://doi.org/10.1186/s12940-022-00863-x.

Ross, C.E., Mirowsky, J., 2009. Neighborhood disorder, subjective alienation, and distress. J. Health Soc. Behav. 50, 49–64. https://doi.org/10.1177/002214650905000104.

Schikowski, T., Altuğ, H., 2020. The role of air pollution in cognitive impairment and decline. Neurochem. Int. 136, 104708. https://doi.org/10.1016/j.neuint.2020.104708.

Schikowski, T., Vossoughi, M., Vierkötter, A., Schulte, T., Teichert, T., Sugiri, D., et al., 2015. Association of air pollution with cognitive functions and its modification by APOE gene variants in elderly women. Environ. Res. 142, 10–16. https://doi.org/10.1016/j.envres.2015.06.009.

Shen, Y., de Hoogh, K., Schmitz, O., Clinton, N., Tuxen-Bettman, K., Brandt, J., et al., 2022. Europe-wide air pollution modeling from 2000 to 2019 using geographically weighted regression. Environ. Int. 168, 107485. https://doi.org/10.1016/j.envint.2022.107485.

Shen, B., Mode, N.A., Noren, Hooten N., Pacheco, N.L., Ezike, N., Zonderman, A.B., et al., 2023. Association of race and poverty status with DNA methylation–based age. JAMA Netw. Open 6, e236340. https://doi.org/10.1001/jamanetworkopen.2023.6340.

Son, J.-Y., Choi, H.M., Fong, K.C., Heo, S., Lim, C.C., Bell, M.L., 2021. The roles of residential greenness in the association between air pollution and health: a systematic review. Environ. Res. Lett. 16, 093001. https://doi.org/10.1088/1748-9326/ac0e61.

Steptoe, A., Zaninotto, P., 2020. Lower socioeconomic status and the acceleration of aging: an outcome-wide analysis. Proc. Natl. Acad. Sci. USA 117, 14911–14917. https://doi.org/10.1073/pnas.1915741117.

Thompson, R., Smith, R.B., Karim, Y.B., Shen, C., Drummond, K., Teng, C., et al., 2023. Air pollution and human cognition: a systematic review and meta-analysis. Sci. Total Environ. 859, 160234. https://doi.org/10.1016/j.scitotenv.2022.160234.

Vaupel, J.W., 2010. Biodemography of human ageing. Nature 464, 536–542. https://doi.org/10.1038/nature08984.

Veronese, N., Soysal, P., Demurtas, J., Solmi, M., Bruyère, O., Christodoulou, N., et al., 2023. Physical activity and exercise for the prevention and management of mild cognitive impairment and dementia: a collaborative international guideline. Eur Geriatr Med 14, 925–952. https://doi.org/10.1007/s41999-023-00858-y.

Wang, M., Zhou, X.-H.A., Curl, C., Fitzpatrick, A., Vedal, S., Kaufman, J., 2023a. Long-term exposure to ambient air pollution and cognitive function in older US adults. Environmental Epidemiology 7, e242. https://doi.org/10.1097/EE9.0000000000000242.

Wang, Z., Xu, L., Wang, Y., Li, H., 2023b. Validation of the ten-word test for immediate memory in middle-aged and older population with subjective cognitive decline and mild cognitive impairment. Alzheimer's Dementia 19. https://doi.org/10.1002/alz.079481.

Woodford, H.J., George, J., 2007a. Cognitive assessment in the elderly: a review of clinical methods. QJM 100, 469–484. https://doi.org/10.1093/qjmed/hcm051.

Woodford, H.J., George, J., 2007b. Cognitive assessment in the elderly: a review of clinical methods. QJM 100, 469–484. https://doi.org/10.1093/qjmed/hcm051.

World Health Organization, 2015. World Report on Ageing and Health. Luxembourg.

World Health Organization, 2021. WHO global air quality guidelines: particulate matter (PM2. 5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. Executive Summary.

Wu, Y.-T., Prina, A.M., Brayne, C., 2015a. The association between community environment and cognitive function: a systematic review. Soc Psychiatry Psychiatr Epidemiol 50, 351–362. https://doi.org/10.1007/s00127-014-0945-6.
Wu, Y.-T., Prina, A.M., Brayne, C., 2015b. The association between community environment and cognitive function: a systematic review. Soc Psychiatry Psychiatr Epidemiol 50, 351–362. https://doi.org/10.1007/s00127-014-0945-6.
Wu, Z., Phyo, A.Z.Z., Al-harbi, T., Woods, R.L., Ryan, J., 2020. Distinct cognitive trajectories in late life and associated predictors and outcomes: a systematic review. J Alzheimers Dis Rep 4, 459–478. https://doi.org/10.3233/ADR-200232.
Zaninotto, P., Batty, G.D., Allerhand, M., Deary, I.J., 1978. Cognitive function trajectories and their determinants in older people: 8 Years of follow-up in the English Longitudinal Study of Ageing. J. Epidemiol. Community Health 72, 685–694. https://doi.org/10.1136/jech-2017-210116, 2018.
Zhang, W., Wu, Y.Y., 2017. Individual educational attainment, neighborhood-socioeconomic contexts, and self-rated health of middle-aged and elderly Chinese: exploring the mediating role of social engagement. Health Place 44, 8–17. https://doi.org/10.1016/j.healthplace.2016.12.006.
Zhang, Q., Schwade, M., Smith, Y., Wood, R., Young, L., 2020. Exercise-based interventions for post-stroke social participation: a systematic review and network meta-analysis. Int. J. Nurs. Stud. 111, 103738. https://doi.org/10.1016/j.ijnurstu.2020.103738.
Zhao, Y.-L., Qu, Y., Ou, Y.-N., Zhang, Y.-R., Tan, L., Yu, J.-T., 2021a. Environmental factors and risks of cognitive impairment and dementia: a systematic review and meta-analysis. Ageing Res. Rev. 72, 101504. https://doi.org/10.1016/j.arr.2021.101504.
Zhao, Y.-L., Qu, Y., Ou, Y.-N., Zhang, Y.-R., Tan, L., Yu, J.-T., 2021b. Environmental factors and risks of cognitive impairment and dementia: a systematic review and meta-analysis. Ageing Res. Rev. 72, 101504. https://doi.org/10.1016/j.arr.2021.101504.
Zijlema, W.L., Triguero-Mas, M., Smith, G., Cirach, M., Martinez, D., Dadvand, P., et al., 2017. The relationship between natural outdoor environments and cognitive functioning and its mediators. Environ. Res. 155, 268–275. https://doi.org/10.1016/j.envres.2017.02.017.