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Railways to better minds: The influence of high-speed rail on cognitive health inequalities

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ABSTRACT

Cognitive impairment has become a major challenge to health aging all over the world, and evidence shows that transportation infrastructure affects the elderly's cognitive health. However, little is known about the effects of high-speed rail (HSR) on cognitive health. Based on the panel data from 2011 to 2018, this study employs the double machine learning (ML) approach to examine the relationship between HSR and cognitive health among 11,572 middle-aged and aged adults in China. The result shows that the opening of HSR significantly improved global cognition, with an estimated treatment effect coefficient of 0.198 (95 % confidence interval, [0.088, 0.309]). The effect of HSR varies in dimensions of cognitive health, only promoting mental intactness rather than episodic memory. The main result remains robust after conducting a series of robustness tests such as introducing instrumental variables, replacing the HSR measurements and ML method. Further analysis shows that HSR has heterogeneous effects on cognitive health across gender, ages, education levels, rural–urban areas, and geographic regions. For instance, HSR has narrowed the cognitive health inequalities between individuals with elementary or middle school education and those with higher education, but widened the gap between rural and urban residents. Additionally, mediation analysis indicates that HSR may enhance cognitive health by reducing PM2.5 exposure, improving individual earnings, and alleviating depressive symptoms. This study provides beneficial insights for China and other countries to develop transportation infrastructure and promote healthy cognitive aging.

1. Introduction

In recent years, demographic aging has become prevalent in many countries (Grinin et al., 2023). This demographic shift has prompted increased attention to the health and well-being of the elderly, with a particular focus on cognitive abilities (Ruiz et al., 2023; Seblova et al., 2020; Skirbekk et al., 2012; Yang et al., 2016). Cognitive decline among the elderly is a critical concern, as it not only affects the individual's quality of life, but also places a substantial burden on the healthcare system (Murman, 2015; Prince et al., 2015). Extensive studies have explored individual factors that are protective of cognitive health of older adults, such as socioeconomic status (Ruiz et al., 2023; Yang et al., 2016), access to healthcare (Mullins et al., 2021), employment opportunities (Luo et al., 2019), health behaviors, social engagement (Hwang et al., 2018), and positive childhood experiences (Lee and Schafer, 2021). Additionally, environmental factors like green space exposure and traffic-related air pollution have been shown to influence cognitive health in later life (Power et al., 2011; L. Zhang et al., 2022). However, despite this extensive body of research, the role of transportation infrastructure, particularly high-speed rail (HSR), in influencing cognitive health has received little attention. HSR was first introduced in Japan in 1964 (Takatsu, 2007) and has since expanded to other countries such as France (Vickerman, 1997), Spain (Sánchez-Borràs et al., 2011), and Germany (Heuermann and Schmieder, 2019). In 2010, China began an extensive phase of HSR construction (Ke et al., 2017), and its rapid adoption, coupled with the

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country's ongoing demographic aging, provides a unique opportunity to study the potential effects of transportation infrastructure on the cognitive health of middle-aged and older adults.

Given that the impact of HSR on cognitive health, particularly among middle-aged and older adults, remains underexplored, this study aims to fill this gap by utilizing nationally representative data and a double machine learning (DML) approach to examine the effects of HSR on the cognitive health of middle-aged and older individuals in China. Moreover, this research will analyze the heterogeneity of these effects across gender, ages, education levels, rural–urban divides, and geographic regions, as well as the underlying mechanisms through which these effects operate.

This study makes several key contributions as follows: First, by focusing on the relationship between HSR and cognitive health among middle-aged and older adults, it addresses a critical but underexplored area in both cognitive aging and transportation research. While previous studies have emphasized the economic and environmental impacts of HSR, limited attention has been paid to its potential health externalities, particularly in relation to cognitive aging. Our findings suggest that HSR can serve as a structural determinant of cognitive health. Second, this study develops an integrative theoretical framework to explain the mechanisms through which HSR affects cognitive health. This multidisciplinary framework draws on insights from social epidemiology, transportation, and gerontology studies, offering a comprehensive perspective on how infrastructure shapes cognitive health in later life. Third, the study uncovers important heterogeneity in the cognitive health effects of HSR across subpopulations. For instance, HSR appears to narrow cognitive health disparities between individuals with elementary or middle school education and those with higher education, while widening the gap between rural and urban residents. Fourth, we employ a DML approach and instrumental variables to estimate causal effects, addressing endogeneity concerns and improving robustness.

The rest of this study is structured as follows: Section 2 proposes the theoretical framework and research hypotheses. Section 3 introduces the data sources, variables, and empirical strategies. Section 4 presents and interprets the main findings. Section 5 summarizes the study and discusses the implications of the findings. Section 6 concludes by offering policy recommendations based on the results.

2. Research hypotheses

HSR represents a transformative mode of transportation that enhances connectivity and accessibility, which are crucial for the cognitive health of middle-aged and older adults. This study proposes a theoretical framework that integrates both individual and environmental protective factors of cognitive health with the potential influence of HSR on middle-aged and older populations. At the individual level, key determinants such as access to healthcare, economic situation and mental health have long been established as critical for maintaining cognitive health. On the environmental level, reduced exposure to air pollutants is recognized as important contributor to cognitive health. Building on prior research, we propose that HSR may influence cognitive health through four pathways: Environmental improvement, enhanced healthcare access, economic advancement, and mental health improvement, as illustrated in Fig. 1. First, HSR contributed to improved air quality (Guo et al., 2020; Zhao et al., 2021), and this environmental benefit is positively associated with the cognitive health of individuals. Second, HSR improves access to healthcare facilities (Bu et al., 2022; Liu et al., 2021; Song et al., 2021), allowing individuals to reach high-quality medical services. Evidence shows that better access to healthcare is more likely to engage in preventive care and receive timely interventions, which can mitigate cognitive decline (Mullins et al., 2021). Third, HSR promotes industrial updating and economic growth (Fan and Xu, 2023; Huang and Wang, 2020; Liang et al., 2020; Meng et al., 2018), creating more employment opportunities and improving income. Lastly, reduced travel time as a significant benefit of HSR, not only facilitates mobility but also promotes mental health by fostering social interaction and engagement (Gong et al., 2021; Liu and Zhang, 2018), which is essential for supporting cognitive health. Based on the discussion above, the following hypothesis is proposed.

Hypothesis 1. HSR can improve cognitive health of middle-aged and older adults.

The effects of HSR on cognitive health are likely to exhibit considerable heterogeneity across different groups, influenced by various factors such as gender, ages, education levels, rural–urban divides, and geographic regions. For instance, studies indicate that women generally experience higher rates of cognitive decline compared to men, largely due to their longer life expectancy and differing social roles, which may lead to greater social isolation in later years (Levine et al., 2021). This suggests that the cognitive health benefits of HSR may be particularly pronounced for middle-aged and older women, as improved transportation options could facilitate social interactions and reduce mental disorders. Education level is another significant determinant of cognitive health, as higher educational attainment is linked to greater cognitive reserves, which can enhance resilience against cognitive decline (Avila et al., 2009; Bennett et al., 2003; Seblova et al., 2020). Individuals with higher education may be more likely to engage with healthcare services and participate in cognitive-stimulating activities, thereby maximizing the potential benefits of improved transportation access. Moreover, regional differences in infrastructure, healthcare access, and social services can further compound these effects, leading to varied outcomes in cognitive health among different populations. For example, urban middle-aged and older adults might benefit from HSR in terms of reduced travel time to essential services, while rural populations might gain more substantial benefits from access to previously unreachable healthcare and social opportunities. This gap may further contribute to cognitive differences across various groups of middle-aged and older adults. Based on these discussions, the following hypothesis is proposed.

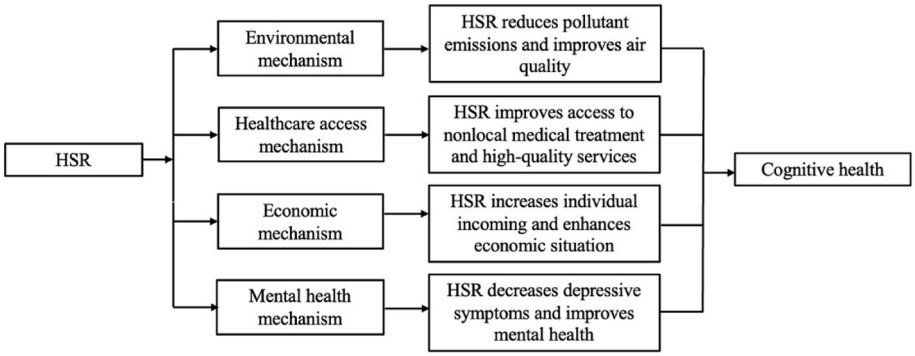

Fig. 1. Potential mechanisms of cognitive health effect of HSR

Hypothesis 2. There is heterogeneity in the impact of HSR on cognitive health of middle-aged and older adults.

Prior research has consistently demonstrated that long-term exposure to fine particulate matter (PM2.5) is significantly associated with cognitive decline, particularly among older adults (Grande et al., 2021; Weuve et al., 2012; Ye et al., 2023). Mechanistically, air pollutants contribute to systemic inflammation and cerebrovascular dysfunction, both of which are implicated in neurodegenerative processes (Peters et al., 2019; Power et al., 2011). Recent empirical studies in the context of China provide quasi-experimental evidence that the opening of HSR lines contributes to reductions in local PM2.5 concentrations (Chang et al., 2021; Su and Xie, 2023). These environmental gains are particularly salient in regions with higher industrial density and greater market responsiveness. Bridging these two strands of literature, we propose that HSR-induced environmental improvements, specifically the reduction of air pollutants, may positively influence cognitive health.

Hypothesis 3. HSR can improve cognitive health of middle-aged and older adults by reducing air pollutants.

In the context of China's rapidly expanding intercity transportation network, HSR has emerged as a critical enabler of patient mobility, particularly for populations in remote or medically underserved regions. Recent studies indicate that HSR significantly facilitates access to higher-tier hospitals, allowing individuals to bypass local limitations in medical infrastructure and seek specialized care in nonlocal areas (Liu et al., 2021; Zhang et al., 2023). This improved spatial accessibility helps reduce regional disparities in healthcare utilization and enhances the overall quality of care received. For middle-aged and older adults, who are vulnerable to delayed or inadequate treatment, early and accurate diagnosis of cognitive impairment is essential. HSR may indirectly support cognitive health by making it easier for individuals to access neurological care and diagnostic services. Drawn on these discussions, the following hypothesis is proposed.

Hypothesis 4. HSR can enhance cognitive health of middle-aged and older adults by improving access to healthcare.

A growing body of evidence demonstrates that HSR significantly enhances individual economic outcomes, including per-capital disposable income (Jin et al., 2022) and wage levels (Liu and Yang, 2023; Wang et al., 2024). These economic gains are largely attributed to improved labor mobility and market access facilitated by HSR. Additionally, previous evidence underscores the importance of socioeconomic status, particularly income, as a key determinant of cognitive health in older age (Muhammad et al., 2021; Rodriguez et al., 2021). The economic benefits brought by HSR may indirectly support healthy cognitive aging by increasing income levels. Built on these discussions, the following hypothesis is proposed.

Hypothesis 5. HSR can improve cognitive health of middle-aged and older adults by enhancing individuals' economic situation.

Compared to conventional rails, HSR substantially increases travel accessibility and reduces time costs, thereby enabling more frequent and meaningful social interactions across spatially distant locations (Chen and Chen, 2023; Yang et al., 2025). Enhanced mobility facilitates a broader range of leisure and tourism activities, which have been shown to promote both mental health and cognitive functioning (Sala et al., 2019; Sun and Lin, 2018; Wang et al., 2025). A growing literature has identified mental health as a key determinant of cognitive performance in aging populations (Bunce et al., 2008; Donovan et al., 2017). In particular, depression is closely linked to cognitive decline and are known to exacerbate age-related memory and executive dysfunction (Biringer et al., 2005; Weisenbach et al., 2012). By reducing spatial isolation and encouraging intercity visitation and social interaction, HSR may mitigate these psychological stressors. Integrating the above discussion, we propose the following hypothesis.

Hypothesis 6. HSR can promote cognitive health of middle-aged and older adults by enhancing mental health.

3. Data and method

3.1. Data

3.1.1. Data description

This study used the nationally longitudinal survey data of the China Health and Retirement Longitudinal Study (CHARLS) fielded in 2011, 2013, 2015, and 2018. CHARLS encompasses more than 17,500 participants aged 45 and above in 150 counties and 450 villages or resident committees (Zhao et al., 2014). Its questionnaire includes rich information about demographics, family structure, health status and functioning, and other modules. CHARLS was approved by the Ethics Committee of Peking University.

In this study, we created the indicators of cognitive abilities using data from CHARLS. To measure the exposure to HSR, we also identified the prefecture-level cities where CHARLS participants reside and integrated this data with the information on the operational status of HSR. The HSR data was manually compiled using information from the National Railway Administration of the People's Republic of China and China State Railway Group Co., Ltd. We included participants who are aged $\geq$45 years and continuously were interviewed from CHARLS wave 1 (2011) to wave 4 (2018), and the missing values of dependent variables and independent variables are less than 30 %, as Fig. 2 shows. Missing values for continuous variables were imputed using the median, and for categorical variables, the mode was used.

3.1.2. Measurements

Following prior studies (Luo et al., 2021; Yang et al., 2020), this study measures the global cognition score by summing episodic memory score and mental intactness score, with a total score ranging from 0 to 30. The score of episodic memory is the average of immediate and delayed recall scores, ranging from 0 to 20. Immediate recall score indicates the number of words that participants can immediately recall correctly from ten Chinese words. Delayed recall score reflects the number of words that participants can recall correctly from ten Chinese words after a delay. The mental intactness score was the sum of four tasks including serially subtracting 7 from 100, redrawing a picture, naming the day of the week, and naming the current date (day of month, month, year, and day of week), with scores ranging from 0 to 10.

We created a set of indicators to measure the operational status of HSR. Referring to a previous study (Tang et al., 2021), we constructed a binary variable 'HSR opening' to reflect whether a city has opened a HSR for the first time. This variable is assigned a value of 1 after a city opens HSR and a value of 0 before the opening. Additionally, to comprehensively measure the accessibility to HSR, we also developed two other indicators for robust analysis in this study: 'HSR service frequency', calculated by the number of HSR services, and 'HSR network centrality', which reflects the position of a city in the HSR network. Following the previous study (Tang et al., 2021), we calculated the metric of 'HSR network centrality' by $C_D(N_i) = \sum_{j=1}^{g} x_{ij}(i \neq j)$ where i represents the HSR node, j indicates the city, and g represents the number of HSR nodes. $C_D(N_i)$ represents the degree centrality of HSR node i, which represents the number of HSR connections between node i and other $g-1$ nodes. We selected degree centrality over other centrality indicators because it captures the number of direct HSR connections a city has with other cities, which is particularly relevant for older adults whose mobility often depends on simple and direct travel routes.

Strong evidence has demonstrated that cognitive health in later life is associated with a range of life-course factors (Brewster et al., 2014; Lyu and Burr, 2016). Therefore, the study included a wide range of life-course factors as control variables, including demographics (gender,

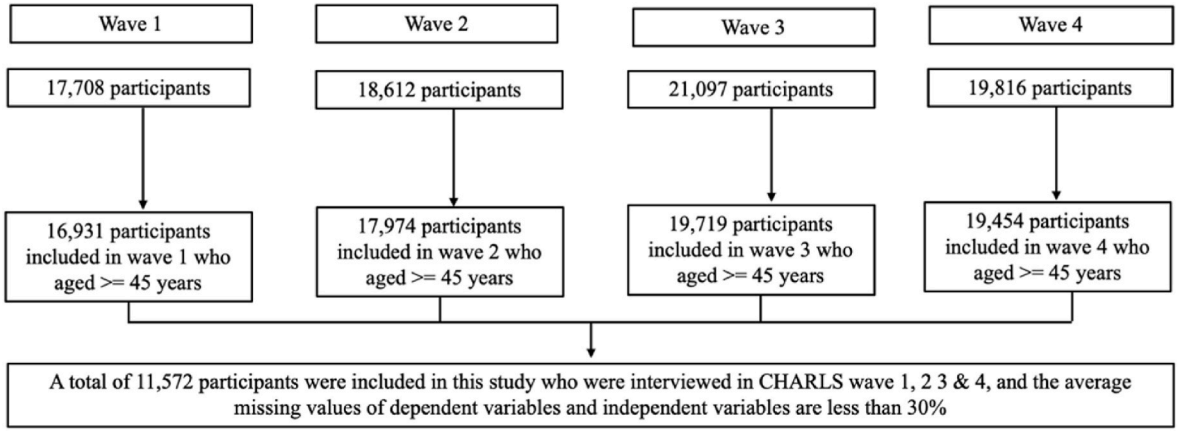

Fig. 2. Flow chart of the analytic sample.

age, marriage, education, living in a rural area), physical health status (self-reported health, difficulty with activities of daily living, difficulty with mobility activities), health behaviors (whether ever drank, whether ever smoked), family structure (co-residing with children, living near children, experiencing child death), social connections (weekly contacting with children, social activities in the past month), and childhood circumstances (father education level, father occupational type, mother occupational type, self-reported health during childhood, family financial status during childhood). Additionally, based on previous studies (Song et al., 2021; Yang et al., 2025), we selected city-level control variables, including the percentage of foreign direct investment in GDP, population density, and the percentage of education expenditure in local government fiscal spending. Table S1 in supplementary materials illustrates the detailed information on the control factors.

To address potential endogeneity, we conducted an instrumental variables (IV) analysis. An ideal instrument should be correlated with the likelihood of HSR construction in a given city but should not directly affect the residents' cognitive health, hence satisfying the relevance and exclusion restriction criteria. In our study, we selected three geographic factors and one historical railway variable as instruments. Specially, we used topographic relief, average slope and average elevation of each city, which has been tested in other studies (Bu et al., 2022; Tang et al., 2023; Xiong et al., 2023; Yang et al., 2021, 2022). These geographical factors will influence the feasibility and cost of rail infrastructure, but not directly influence residents' cognitive health. Additionally, following previous studies using historical railway variables as instruments for HSR (Diao, 2018; Miwa et al., 2022; Wang et al., 2025; Xiong et al., 2023; Zheng and Kahn, 2013), we used the opening of railway in 1933 as an instrument. This variable captures long-term path dependence in transportation planning and is strongly associated with modern HSR placement, but it is unlikely to be directly related to current residents' cognitive health.

To investigate the mechanisms through which HSR influences cognitive health, we introduced five potential mediators: PM2.5 exposure (air pollutants), individual earnings (economic situation), depressive symptoms (mental health), and two indicators of healthcare access–nonlocal medical treatment and the type of healthcare institutions. PM 2.5 exposure was measured by the natural logarithm of the annual total PM 2.5 concentration to reflect air pollution pollutants. Depressive symptoms were assessed using the CES-D scale (ranging from 0 to 30), with lower scores indicating better mental health. Individual earnings were measured as the natural logarithm of individual after-tax earnings, indicating economic situation. Nonlocal medical treatment was defined based on the location of healthcare access, indicating whether healthcare was received within the individual's county or city, or outside the individual's home province, city or county, indicating spatial access to healthcare services. The type of healthcare institutions was classified into low-tier (e.g., community healthcare centers, township hospitals, health care posts and others) and high-tier institutions (e.g., general or specialized hospitals), serving as a proxy for access to higher-quality healthcare.

3.2. Method

Double machine learning (DML) is a novel model for causal inference analysis, developed by Chernozhukov et al. (2018). The basic idea of the model is using machine learning (ML) algorithms to achieve unbiased estimates, considering the adjustment of potential confounders and complex non-parametric functions (Fuhr et al., 2024). It is challenging for traditional statistical models to handle a large number of confounders, which is known as the 'curse of dimensionality' and may cause multicollinearity and overfitting. And it may be hard for parametric functions to satisfactorily capture the effect of many confounders on a dependent variable. By including ML algorithms within DML, these two potential problems can be handled, hence estimating the treatment effects more accurately in causal inference analysis.

Several studies from various disciplines have employed DML to assess the effect of special supplemental nutrition program, official development assistance and issuance of green bonds (Cheng and Wu, 2024; Guo et al., 2024; Peet et al., 2023). The potential of DML has been demonstrated to foster the development of policy evaluation. Hence, employing DML in this study will provide further understanding of the effect of HSR opening in cognitive health in the context of population aging.

In this study, we examined the effect of HSR on cognitive health in later life. We faced challenges due to underlying multicollinearity among a large number of control variables and potential nonlinear relationships between control variables and cognitive health. Unlike traditional linear regression, DML can effectively solve the issues, which allowed us to obtain more robust and reliable results. Therefore, we used DML in this study. To investigate the impact of HSR on the cognitive health of middle-aged and older adults in China, a partially linear DML model was constructed as Eq. (1) and Eq. (2) shows where i means individuals, t indicates year, CH means cognitive health of middle-aged and older adults, HSR means the operational status of HSR service, X_{it} means control variables, $g(X_{it})$ and $m(X_{it})$ mean the specific form identified by ML, U_{it} and V_{it} means error term. In addition, we used 3-fold cross-validation to ensure the generalization ability of the model. Gradient boosting model was selected as the primary model to conduct regression predictions for both the dependent variable (cognitive health of middle-aged and older adults) and the treatment variable (whether the city opened the HSR service). For robustness check, we also used lasso as an alternative to gradient boosting. These ML models can capture nonlinear relationships and hence promote the prediction

performance. In addition, we obtained the estimated coefficient by performing linear regression on the residuals and the final average estimated coefficients were derived after repeating the process across the 3 folds. This approach integrates the predictive ability of ML with the accurate estimation capability of linear regression. These efforts help mitigate biases in evaluating the influence of HSR on cognitive health of middle-aged and older adults. The empirical analysis was conducted in Stata, version 18.0, with a 95 % confidence interval.

$$CH_{it} = \theta_0 HSR_{it} + g(X_{it}) + U_{it}, E(U_{it}|X_{it}, HSR_{it}) = 0 \quad (1)$$

$$HSR_{it} = m(X_{it}) + V_{it}, E(V_{it}|X_{it}) = 0 \quad (2)$$

4. Results

4.1. Descriptive statistics

Demographic characteristics of participants in the baseline survey (2011) are summarized in Table 1. The mean value of the global cognition score is 14.98, with mean scores of 7.20 for episodic memory and 7.51 for mental intactness. Participants' ages range from 45 to 75+ years old, with 61 % being middle-aged individuals (45–60 years) and 39 % being older adults (60 years and above). The majority of the participants are females (54 %), married or partnered (90 %), and have an education level of elementary school or below (69 %). Additionally, 67 % of participants have never drunk alcohol, 61 % have never smoked, 65 % reside in rural villages, and 71 % live in Eastern and Central China. Additionally, HSR coverage steadily increased across the survey period, rising from 24.36 % of participants living in cities with HSR access in 2011 to 73.77 % in 2018, highlighting the rapid expansion of this transport infrastructure in China during these years.

4.2. Effects of HSR on cognition

Table 2 shows the DML model estimating the effect of HSR opening on the global cognitive. In Table 2, time fixed effects and individual fixed effects are added incrementally. The results revealed that the coefficient of HSR opening was 0.198, which is significantly positive and passes the statistical significance test. This indicates that HSR opening has a beneficial influence on the cognitive health of the residents in cities where HSR services were initiated. Therefore, we confirmed Hypothesis 1: HSR can enhance cognitive health of middle-aged and older adults.

We further examined the impact of HSR opening on two key components of global cognition: episodic memory and mental intactness, as Table 3 shows. The result shows that HSR opening significantly improved the performance of mental intactness. However, the introduction of HSR service did not appear to have a significant effect on episodic memory.

To examine the lagged effects of HSR on cognitive health, we test the one- and two-period lags of HSR opening. As shown in Table S2 in supplementary materials, both coefficients remain positive and significant, indicating robust results. Moreover, the estimated effect of 0.302 slightly increases from the first lag (95 % CI, [0.162, 0.442]) to the second lag (estimated effect = 0.303, 95 % CI, [0.092, 0.514]), suggesting that the cognitive benefits of HSR access are not only sustained but may also strengthen over time.

4.3. Robust analysis

This study employed several strategies to check the robustness of our results, as detailed in Table 4. First, we addressed potential endogeneity concerns by using four instrumental variables. The result shows that the coefficients of HSR are still significant, suggesting that endogeneity is unlikely to bias our findings. Second, we increased the number of cross-validation folds from 3 to 5 and 7. In both cases, the estimated

Table 1
Demographic characteristics of participants and HSR over time (2011–2018).

Variables	N (%)/Mean ± SD (Min-Max)			
	2011	2013	2015	2018
Cognition				
Global cognition	14.98 ± 4.00 (0–30)	15.15 ± 4.03 (0–30)	14.59 ± 4.28 (0–30)	15.61 ± 4.10 (0–29)
Episodic memory	7.20 ± 3.02 (0–20)	7.25 ± 3.22 (0–20)	6.55 ± 3.52 (0–20)	7.00 ± 3.86 (0–19)
Mental intactness	7.51 ± 2.18 (0–10)	7.62 ± 2.02 (0–10)	7.54 ± 2.07 (0–10)	7.52 ± 1.79 (0–10)
Gender				
Male	5541 (46 %)	5541 (46 %)	5541 (46 %)	5541 (46 %)
Female	6447 (54 %)	6447 (54 %)	6447 (54 %)	6447 (54 %)
Age				
45–60	7314 (61 %)	6309 (53 %)	5159 (43 %)	3799 (32 %)
60–75	4092 (34 %)	4829 (40 %)	5639 (47 %)	6368 (53 %)
>75	582 (5 %)	850 (7 %)	1154 (10 %)	1821 (15 %)
Marriage				
Married or partnered	10731 (90 %)	10575 (88 %)	10360 (86 %)	9931 (83 %)
separated, divorced, widowed, never married	1257 (10 %)	1413 (12)	1628 (14 %)	2057 (17 %)
Education				
No formal education, illiterate	3315 (28 %)	3315 (28 %)	3315 (28 %)	3315 (28 %)
Did not finish primary school but capable of reading and/or writing, Sishu	2222 (19 %)	2222 (19 %)	2222 (19 %)	2222 (19 %)
Elementary school	2615 (22 %)	2615 (22 %)	2615 (22 %)	2615 (22 %)
Middle school	2508 (21 %)	2508 (21 %)	2508 (21 %)	2508 (21 %)
High school and above	1328 (11 %)	1328 (11 %)	1328 (11 %)	1328 (11 %)
Drink				
Yes	3990 (33 %)	4146 (35 %)	4052 (34 %)	3772 (31 %)
No	7998 (67 %)	7842 (65 %)	7934 (66 %)	8216 (69 %)
Smoke				
Yes	4636 (39 %)	5057 (42 %)	5250 (44 %)	5098 (43 %)
No	7352 (61 %)	6931 (58 %)	6738 (56 %)	6890 (57 %)
Rural–urban areas				
Rural village	7840 (65 %)	7840 (65 %)	7840 (65 %)	7840 (65 %)
Urban community	4148 (35 %)	4148 (35 %)	4148 (35 %)	4148 (35 %)
Region				
Eastern China	4839 (40 %)	4839 (40 %)	4839 (40 %)	4839 (40 %)
Central China	3747 (31 %)	3747 (31 %)	3747 (31 %)	3747 (31 %)
Western China	3402 (28 %)	3402 (28 %)	3402 (28 %)	3402 (28 %)
HSR coverage (%)	24.36 %	40.94 %	60.59 %	73.77 %

Note: Outcome variables are presented as mean ± standard deviation (SD), with minimum and maximum values shown in parentheses. For categorical variables, frequencies and percentages are reported in the format N (%). Additionally, HSR coverage refers to the proportion of participants living in cities that had operational HSR service in a given survey year. Based on the city-level matching of the HSR opening year, we calculated the proportion of participants living in HSR-covered areas at the time of each survey.

Table 2
Impact of HSR opening on global cognition.

Variable	(1)	(2)	(3)	(4)
	Global cognition	Global cognition	Global cognition	Global cognition
HSR opening	0.338*** [0.238, 0.437]	0.163** [0.053, 0.273]	0.371*** [0.272,0.471]	0.198*** [0.088, 0.309]
Time Fixed Effects		Control		Control
Individual Fixed Effects			Control	Control

Note: Values in brackets indicate 95 % confidence intervals. ***p < 0.001, **p < 0.01, *p < 0.05.

Table 3
Impact of HSR opening on mental intactness and episodic memory.

Variable	Mental intactness	Episodic memory
HSR opening	0.111*** [0.053,0.170]	0.086 [-0.005, 0.176]
Time Fixed Effects	Control	Control
Individual Fixed Effects	Control	Control

Note: Values in brackets indicate 95 % confidence intervals. ***p < 0.001, **p < 0.01, *p < 0.05.

coefficients for HSR remained significantly positive, confirming the robustness of our findings. Third, we changed the ML methods used in our study, from gradient boosting to lasso. The result for lasso was consistent with those for gradient boosting. Lastly, we replaced the key independent variable HSR opening with HSR service frequency and HSR network centrality, which more comprehensively measure the accessibility to HSR. The results demonstrated that the coefficients are still significantly positive. In sum, after a series of robust analyses, the effects of HSR on cognitive health among Chinese middle-aged and old adults remain robust.

4.4. Heterogeneous effects

Considering the heterogeneity across different genders, education levels, age, rural–urban areas, and regions, we further examined the heterogeneous effects of HSR opening, as shown in Fig. 3. There are gender-specific impacts of HSR opening on the global cognition of middle-aged and older adults in China. The opening of HSR has a positive effect on global cognition for both male and female individuals. However, the effect size is larger and only statistically significant for female middle-aged and aged adults. When examining the urban-rural heterogeneous impacts of HSR opening on global cognition, we found that the effect size is larger and significant only for urban residents. Considering regional heterogeneity, HSR opening had a positive impact across the three regions, with the greatest effect observed in Eastern China individuals, followed by those in Central and Western China, though the effect is only significant for Eastern China individuals. There is distinct heterogeneity across ages as well, with HSR opening significantly improving the global cognition of young-old individuals (60–74), but not significantly influencing the global cognition of the middle-aged (age 45–59) and old-old (age 75 and over) individuals. Additionally, examining the education heterogeneity, we found that, the individuals with elementary and middle school education significantly benefited from HSR opening, while the effects for those with either lower or higher levels of education were not statistically significant. Therefore, we confirmed Hypothesis 2, demonstrating that the impact of HSR on the cognitive health of middle-aged and older adults is heterogeneous across different groups.

4.5. Mediating effects

Table 5 presents the mediating effects of PM2.5 exposure, individual earnings, depressive symptoms, nonlocal medical treatment, and the type of medical institutions between HSR opening and cognitive health among middle-aged and older adults. A significant mediating effect was observed through decreasing PM2.5 exposure, with an indirect effect of 0.051 ($p < 0.001$), suggesting that improved air quality following the operation of HSR partially accounts for the observed cognitive health benefits. This supports Hypothesis 3, demonstrating that HSR improves the cognitive health of middle-aged and older adults by mitigating air pollution. By contrast, nonlocal medical treatment and the type of medical institutions did not exhibit significant mediating effects, despite their positive indirect estimates, which does not support Hypothesis 4. Individual earnings have a smaller but statistically significant mediating effect (indirect effect = 0.009, $p < 0.05$), implying that enhanced economic situation may also play a role in promoting cognitive health. It supports Hypothesis 5, revealing that HSR can improve the cognitive health of middle-aged and older adults by enhancing their economic situation. Depressive symptoms also significantly mediated the association, with an indirect effect of 0.038 ($p < 0.001$), indicating that alleviation of depressive symptoms may be one mechanism through which HSR supports cognitive functioning. Therefore, we confirmed Hypothesis 6, demonstrating that HSR promoted the cognitive health of middle-aged and older adults by enhancing psychological well-being. These results underscore the importance of environmental, economic, and mental health pathways in shaping the cognitive benefits of HSR.

We further tested robustness by estimating lagged mediation models (Table S3 in supplementary materials). The main findings that HSR improves cognitive health through environmental, economic, and mental health remains robust, while the time dynamics of specific

Table 4
Impact of HSR on global cognition.

Variable	Global Cognition								
	Instrumental Variables				Change Cross-Validation Folds		Change ML Model	Replacing HSR Measurements	
	Topographic Relief	Average Slope	Average Elevation	Opening of the Railway in 1933	5-Folds	7-Fold	Lasso	HSR Frequency	HSR Centrality
HSR	3.051*** [1.762, 4.341]	7.257** [2.957, 11.557]	24.981* [0.010, 49.951]	0.577* [0.087, 1.067]	0.213*** [0.102, 0.324]	0.195** [0.085, 0.305]	0.105* [0.013,0.196]	0.001** [0.0003, 0.0015]	0.0002* [0.00003, 0.00032]
Time Fixed Effects	Control	Control	Control	Control	Control	Control	Control	Control	Control
Individual Fixed Effects	Control	Control	Control	Control	Control	Control	Control	Control	Control

Note: Values in brackets indicate 95 % confidence intervals. ***p < 0.001, **p < 0.01, *p < 0.05.

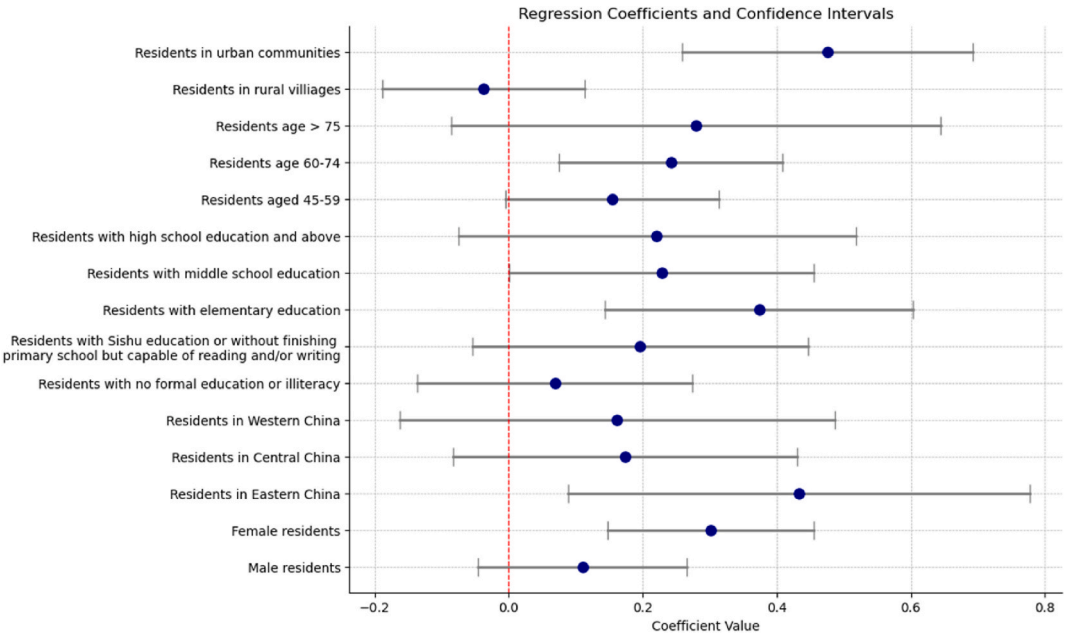

Fig. 3. Heterogeneous impacts of HSR opening on global cognition.

Table 5
Mediation effects of HSR opening on global cognition.

Effect	PM2.5 Exposure	Individual Earnings	Depressive Symptoms	Nonlocal Medical Treatment	Type of Medical Institutions
Total effect	0.183*** [0.096, 0.271]	0.183*** [0.096, 0.271]	0.183*** [0.096, 0.271]	0.283* [0.022, 0.545]	0.281* [0.027, 0.535]
Direct effect	0.190*** [0.100, 0.280]	0.163*** [0.075, 0.251]	0.143** [0.055, 0.230]	0.293* [0.029, 0.556]	0.277* [0.024, 0.530]
Indirect effect	0.051*** [0.034, 0.069]	0.009* [0.001, 0.016]	0.038*** [0.026, 0.050]	0.002 [-0.014, 0.018]	0.016 [-0.013, 0.045]

Note: Values in brackets indicate 95 % confidence intervals. ***p < 0.001, **p < 0.01, *p < 0.05.

mediators vary. The mediator PM2.5 exposure shows a clear attenuation over time, suggesting that air-quality improvements generate relatively immediate cognitive gains that diminish as the post-opening period extends. In contrast, the individual earnings channel strengthens with delay, which is consistent with cumulative income effects, as resources and investments that support cognition accumulate over time. Depressive symptoms display a nonlinear pattern, implying short-term psychological relief followed by stronger long-term mental health benefits. Mediation through nonlocal medical treatment and type of medical institutions remains statistically insignificant across lag structures. These results reinforce the main findings while highlighting distinct temporal profiles for environmental, economic, and psychological mechanisms.

To further extend our analysis of the mediating mechanisms, we included an additional robustness check by examining heterogeneous mediation effects across urban and rural subsamples. As shown in Table S4 in supplementary materials, the mediating effect of the type of medical institutions remains statistically insignificant in both urban and rural subsamples. By contrast, the mediating coefficients of nonlocal medical treatment exhibit a more differentiated pattern. In both urban and rural areas, the indirect effects are positive, indicating that HSR expansion may facilitate greater access to nonlocal healthcare resources. However, statistical significance is only observed in the rural sample (estimated indirect effect = 0.027, 95 % CI [0.002, 0.052]).

5. Discussion

As a large transportation infrastructure, HSR not only improved the regional economy and innovation development (Hanley et al., 2022; Ke et al., 2017; Liang et al., 2020; Yang et al., 2021), but also enhanced the residents' health levels (Bu et al., 2022; Chen et al., 2021; Yang et al., 2025). With the population aging increasing in China and other countries, accurately evaluating the effect of HSR on cognitive health aging becomes increasingly important. Our study not only contributes to the understanding of HSR's impact on cognitive health among middle-aged and older adults, but also exemplifies the application of the advanced ML model in health and transportation research.

To the best of our knowledge, our research is the first prospective study to estimate the cognitive health effects of HSR using DML that combines the predictive ability of ML with the accurate estimation capability of linear regression. We provided further understanding of the relationship between a large transportation and the cognitive health of middle-aged and older adults. First, this study revealed that, on population-level, HSR significantly improved global cognition and mental intactness of Chinese middle-aged and older adults after adjusting for a large number of confounders since cognitive health is influenced by various factors. Second, after conducting an array of robust analyses including using instrumental variables, changing ML method, changing cross-validation folds, and replacing HSR opening with HSR frequency and HSR centrality, our results remain robust. Third, we uncovered the subgroup-level heterogeneity between HSR and cognitive health across gender, ages, education levels, rural–urban areas, and geographic regions. Finally, we examined the mechanisms through which HSR influences cognitive health and identified key mediating pathways. These findings offer robust evidence for understanding and evaluating the broader health implications of HSR in the context of population aging.

By leveraging the longitudinal CHARLS data from wave 1 to wave 4 between 2011 and 2018, we estimated the effects of HSR in global cognition with a coefficient of 0.198. This aligns with existing related studies pointing out the positive effect in self-rated, mental and physical health (Bu et al., 2022; Chen et al., 2021; Yang et al., 2025). The underlying mechanisms were found that HSR had a promoting effect on the global cognition of middle-aged and aged individuals by improving the air quality, enhancing individual earnings, and decreasing depressive

symptoms. We further examined the impact of HSR across different dimensions of cognitive health. It is found that HSR opening significantly improved performance in mental intactness, but not in episodic memory, which may be relatively irreversible. HSR opening may protect episodic memory from being worsening but it is hard to improve it by increasing social and economic connections. Moreover, robustness checks with one- and two-period lag models confirm that these positive effects are not only sustained but also exhibit slight strengthening over time.

Heterogeneity analyses found that HSR opening has a significant effect on women, urban, young-old (60–74 years), and less-educated individuals (those with elementary or middle school education). One possible explanation is that women are more likely to experience higher levels of depressive symptoms (Albert, 2015). As HSR contributes to improved mental well-being, these psychological benefits may translate into more substantial cognitive health gains for women. Further research is needed to fully understand the underlying reasons for this gender difference. In contrast, our findings suggest that the cognitive health benefits of HSR are not yet evident in rural middle-aged and older adults. One possible explanation is that HSR fares are higher than those of conventional rail (Dobruszkes et al., 2022), which may pose a financial barrier for rural middle-aged and older adults, who typically have lower income levels compared to their urban counterparts. As previous research has shown, fares play an important role in individuals' decisions between conventional rail and HSR (Ren et al., 2020). We found that individuals with elementary and middle school education significantly benefit from HSR opening, while the effects for those with either no formal schooling or higher (high school and above) education are not statistically significant. A potential explanation is the ceiling effect (Shaw and Hosseini, 2021): higher-educated individuals may already possess higher baseline cognitive functioning, leaving limited room for additional improvement attributable to HSR-related channels such as enhanced mobility, social interaction, and access to resources. In contrast, individuals with elementary or middle school education typically may have lower initial cognitive levels, meaning that HSR-related improvements in connectivity and resources translate into more substantial cognitive gains. This finding also aligns with cognitive reserve theory (Stern, 2006), which emphasizes that individuals with higher education accumulate greater cognitive resilience, making them less sensitive to marginal environmental changes. Young-old individuals (60–74 years) are more likely to benefit from HSR due to greater availability of leisure time and better physical functioning, as retirement often brings increased time resources and reduced role strain (Kim and Moen, 2002), enabling them to take fuller advantage of the opportunities that HSR provides. Regionally, the cognitive health benefits of HSR decrease from Eastern to Central and Western China, with significant effects observed only in the East. This gradient likely reflects underlying regional disparities in socioeconomic development and access to supportive resources for cognitive health. Residents in less developed Western provinces report greater exclusion from HSR (Ren et al., 2020), and a study shows that HSR-related mental health gains are more evident in the East than in other regions (Yang et al., 2025).

Our findings identified environmental improvement, economic gains, and mental health enhancement as significant mediators of the relationship between HSR and cognitive health, whereas healthcare access does not. In particular, the HSR-induced improvement in air quality appears to benefit cognitive health, consistent with prior studies that HSR expansion can significantly reduce PM2.5 concentration (Chang et al., 2021; Su and Xie, 2023). This environmental benefit aligns with recent evidence suggesting cleaner air from HSR contributes to healthier aging (Yang et al., 2025). Our findings differ from a previous study (Gao et al., 2022), which reported that HSR-related air-quality improvements occurred only in core cities and industrial areas. This discrepancy is likely due to differences in the study period: Gao et al. analyzed 2002–2012, corresponding to the early stage of HSR development, whereas our study focuses on 2011–2018, when the HSR network had expanded more extensively and its broader environmental and health impacts became more pronounced. Similarly, the economic mechanism of increased earnings is in line with prior findings that HSR promotes individual income (Chen et al., 2021; Zhang et al., 2022), and that higher income supports better cognitive health (Muhammad et al., 2021; Rodriguez et al., 2021). Furthermore, we found that reduced depressive symptoms partly mediate the relationship between HSR and cognitive health, reinforcing the existing evidence linking HSR development with a lower risk of depression (Yang et al., 2025), and supporting the well-established association between late-life depression is associated with poorer cognitive functioning (Stafford et al., 2024; Weisenbach et al., 2012). In contrast, the healthcare access mechanism did not exhibit a significant mediating effect in the overall sample, despite prior findings that HSR enhances access to medical services (Choi et al., 2019; Liu et al., 2021). A potential explanation lies in limited public awareness and understanding of cognitive impairment among middle-aged and older adults. Cognitive decline is often perceived as a natural part of aging rather than a condition that requires medical attention (Cahill et al., 2015), and severe cognitive impairments such as dementia are frequently associated with stigma in China (Jia et al., 2022). These factors may reduce proactive healthcare-seeking behaviors for cognitive concerns, thereby weakening the role of healthcare access as a mediating pathway in our study. Furthermore, in our heterogeneity analysis, we found the estimated mediating coefficients of nonlocal medical treatment were positive in both rural and urban residents, but statistically significant only among rural residents who previously faced higher barriers to reaching high-quality medical institutions (Zhang et al., 2017). This finding underscores the role of HSR in reducing rural-urban healthcare inequalities by improving connectivity for populations that were historically underserved. One possible explanation involves cognitive reserve: rural residents, who often have lower baseline cognitive reserve due to limited educational and socioeconomic opportunities (Chen et al., 2022), may benefit more from improved access to high-quality healthcare. HSR reduces transportation barriers to nonlocal medical treatment, enabling these residents to receive timely interventions and preventive care that support cognitive health. In contrast, urban residents typically have higher cognitive reserve and are already in closer proximity to medical facilities (Robbins et al., 2019), so additional improvements in access via HSR may translate into minimal cognitive gains, resulting in an insignificant mediating effect. Additionally, robustness checks using lagged mediation models confirm the robustness of our main findings, while revealing distinct temporal patterns across pathways. The environmental benefits of air-quality improvement attenuate over time, the economic effects of higher earnings strengthen with delay, and depressive symptoms follow a nonlinear trajectory.

This study offers new empirical evidence on the cognitive health implications of HSR development. By situating cognitive aging within the context of structural mobility infrastructure, we contribute to an emerging interdisciplinary understanding of how transportation shapes later-life cognitive health. A key contribution of this study lies in its identification of heterogeneous effects across subgroups. Our results indicate that cognitive gains associated with HSR are more pronounced among women, those with elementary or middle school education, and the young-old individuals. These patterns are consistent with prior evidence suggesting that socially and spatially disadvantaged groups due to their lower baseline levels of mobility, are more likely to benefit from improved transportation options (Liang et al., 2020; Liu et al., 2021).

There are several strengths in this study. Firstly, this study fills a crucial gap in existing research by focusing on the association of HSR with the cognitive health of middle-aged and older adults. Despite their vulnerability, older adults are frequently underrepresented in research on the cognitive health effects of transportation infrastructure. This study addresses this gap by examining how HSR may influence cognitive health among aging populations. Secondly, this study makes a distinctive contribution to the existing literature by employing the DML model

to investigate the relationship between HSR and the cognitive health of individuals in later life. The utilization of a ML approach allows for a more accurate examination of the complex and nonlinear relationship that may be difficult for conventional statistical methods to handle. In addition, we strengthen the identification strategy by employing different instrumental variables, which helps to address potential endogeneity and improve the robustness of causal inference. Lastly, the empirical evidence generated by this research has the potential to inform policymakers, urban planners, and healthcare professionals. By systematically exploring the relationship between HSR and cognitive health, policymakers can make more informed choices regarding the development and implementation of HSR projects, taking into account the potential benefits or risks for the aging population's health.

The study also has some limitations. Cognitive health is a complex variable. The cognition indicators in this study, derived from CHARLS, may not comprehensively and accurately reflect cognitive health, given that the survey data is based on self-reported information, which carries a certain degree of subjectivity compared to clinical cognitive tests. Moreover, this study relies solely on data from China, which limits the generalizability of the findings to other countries where HSR is well-established, such as Japan and France. In addition, although social interaction is a potentially important mediating mechanism, the CHARLS dataset mainly captures local and routine activities (e.g., playing Mahjong, attending community club) rather than long-distance interactions that HSR may promote. This measurement limitation may underestimate the full extent of HSR's impact through enhanced social interaction. Future research should consider incorporating registered cognition-related data from hospitals or government records to improve accuracy, as well as survey instruments that capture broader dimensions of social connectedness, including inter-city and long-distance activities.

6. Conclusion

Our findings suggest that investments in HSR can be viewed not only as economic initiatives but also as public health interventions. As such, policymakers should consider the broader societal benefits of such infrastructure projects. Firstly, the positive impact of HSR on cognitive health underscores the need for integrating health objectives into transportation and urban planning policies. This study demonstrates that HSR can significantly improve cognitive function among middle-aged and older adults, particularly in aspects of mental intactness, and that such benefits are not only sustained but may also strengthen over time.

Moreover, the heterogeneous impacts observed in this study suggest that targeted interventions are necessary. For example, the greater cognitive benefits for females, young-old adults, and individuals with elementary or middle school education indicate that HSR projects could be particularly beneficial if designed to address the specific needs of these groups. Tailored measures, such as ensuring affordable access to HSR services for low-income seniors and developing supportive services at HSR stations (e.g., mobility aids, and healthcare kiosks), may enhance the positive impact on cognitive health.

Lastly, the findings suggest that HSR can play a role in reducing cognitive health disparities between certain demographic groups. Policymakers should ensure equitable access to HSR services across urban and rural areas, as well as among different socioeconomic groups. Subsidizing HSR tickets for older individuals, especially those from low-income or rural backgrounds, could help bridge the gap in access to transportation and healthcare services.

CRediT authorship contribution statement

Xu Zong: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Mingming Guan:** Writing – original draft, Visualization, Validation, Resources, Investigation, Formal analysis, Data curation, Methodology, Project administration, Software, Supervision, Writing – review & editing. **Ye Zhang:** Writing – review & editing. **Guowei Dong:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.socscimed.2025.118624.

Data availability

Data will be made available on request.

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