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Social participation, physical activity, and socioeconomic inequalities in later- life cognition: A 15-country longitudinal study

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Abstract

Background

Socioeconomic inequalities in later-life cognition are well established, but whether potentially modifiable behavioural and social pathways operate similarly across contexts is unclear.

Methods

We analysed harmonised longitudinal data (2010–2022) from the Health and Retirement Study (HRS), English Longitudinal Study of Ageing (ELSA), Survey of Health, Ageing and Retirement in Europe (SHARE), and China Health and Retirement Longitudinal Study (CHARLS). Participants were 24429 adults aged ≥ 50 years. Socioeconomic status (SES) combined education, household income, and household assets; cognition was measured using harmonised 30-point scores. Adjusted linear mixed-effects models estimated cohort-specific associations. We tested effect modification by physical activity and indirect associations through social participation, and pooled estimates using random-effects meta-analysis.

Results

Higher SES was associated with better cognitive function in four cohorts (pooled β = 0.96, 95% confidence interval (CI) 0.17 to 1.75). The SES–physical activity interaction was positive in HRS (β = 0.17, 0.13 to 0.22) and CHARLS (0.155, 0.06 to 0.25), negative in SHARE (−0.11, − 0.16 to − 0.05), and not significant in ELSA (−0.023, − 0.07 to 0.02). Indirect associations through social participation were positive in all cohorts; the pooled indirect effect was 0.093 (0.033 to 0.152), accounting for 10.2% (4.3 to 16.1) of the total association.

Conclusions

The more consistent indirect association through social participation suggests a potentially relevant social pathway. The findings support further investigation of social participation and context-specific physical activity approaches to cognitive inequalities.

Background

Population ageing is altering the distribution of disability and dependence worldwide [1]. Cognitive impairment in later life is a major driver of loss of independence and care needs, and even modest declines in cognitive function can translate into substantial societal and health-system costs [2]. Cognitive ageing, however, is patterned by enduring social inequalities, with socioeconomic disadvantage concentrating cumulative exposures to risk and limiting access to protective resources across the life course [3].

Socioeconomic status (SES) refers to an individual's or household's social and economic position within society, typically measured using indicators such as education, income, wealth/assets, and occupation. SES is consistently associated with cognitive performance and trajectories of cognitive decline [4], which reflects lifelong differences in education, material conditions, and opportunities for cognitive stimulation [5]. Income and wealth shape access to nutritious food, safe neighbourhoods, and access to care [6]; education influences employment opportunities, health literacy, and problem-solving skills [7]; and all three influence exposure to stressors that can affect cognitive health over time.

To develop effective strategies for reducing disparities in cognitive impairment, it is essential to clarify the mechanisms through which SES shapes cognitive outcomes. In this study, we focus on physical activity (PA) and social participation (SP) as two primary, modifiable lifestyle factors, conceptualised and operationalised dynamically across distinct behavioural and structural domains. PA refers to any bodily movement produced by skeletal muscles that requires energy expenditure, which we capture via validated self-reported scales of varying intensities (vigorous, moderate, and mild) across cohorts. In older adults, PA is especially important because it helps maintain physical function and supports vascular health and neuroplasticity [8], thereby functioning as a "biological buffer" that may decouple the link between socioeconomic disadvantage and cognitive decline, potentially acting as a "health equalizer" [9].

Nevertheless, PA is heterogeneous in both form and social context. Leisure-time activity is more common among socioeconomically advantaged groups, whereas occupational activity is often concentrated among disadvantaged groups [10]. While existing evidence suggests these domains yield divergent cognitive returns, longitudinal replication across structurally distinct societies remains scarce

[11]. This leaves a critical, policy-relevant question unresolved: does PA universally mitigate socioeconomic disparities in cognition by buffering SES-related disadvantage, or does it instead widen inequalities because cognitively protective leisure-time activity is structurally more accessible to those with greater resources?

In parallel, social participation represents a second, complementary mechanism, though its theoretical role differs fundamentally from that of PA. We define SP as individual involvement in formal or informal activities that provide social connections outside the home—such as volunteer work, club memberships, or religious activities—harmonised consistently across cohorts. We conceptualise SP as a mediating social pathway through which socioeconomic advantage translates into cognitive protection. Social engagement provides cognitive stimulation, reinforces a sense of purpose, and increases access to information. Because opportunities for SP are heavily shaped by material resources, neighbourhood environments, and social capital [12, 13, 14], SP is more likely to be an outcome of SES that subsequently influences cognition, rather than an independent moderator.

Despite the theoretical plausibility of these dual pathways, empirical findings are inconsistent. Some high-income country cohorts suggest that physical activity significantly narrows SES-related cognitive disparities, whereas several studies in low- and middle-income contexts find null or even opposite effects. The extent to which PA serves as a “health equalizer” versus a “resource amplifier” appears to vary across macroeconomic and welfare systems. Similarly, whether the mediating role of SP operates as a universal social pathway or is context-specific remains insufficiently characterised in cross-national longitudinal data. Most prior studies are confined to single-cohort or single-country designs, making cross-context comparisons difficult due to heterogeneous measurements. This limits inference about whether observed gradients reflect generalisable social processes or features specific to national welfare systems, labour markets, and health-care contexts. Existing longitudinal evidence may also be affected by selection bias and potential reverse causality, as individuals with robust baseline cognitive and physical capacities are more predisposed to maintain active lifestyles.

We searched PubMed and Web of Science for articles published up to August 2025, using terms including “socioeconomic status”, “cognitive function”, “physical activity”, “social participation”, and “older adults”. No large-scale, cross-national studies using rigorously harmonised longitudinal data were identified to reconcile these conflicting international findings. To address these critical gaps, a multi-cohort, cross-national comparison across the USA, Europe, and China is necessary. This approach allows us to harmonise parallel longitudinal data and compare the behavioural and social pathways linking SES to cognition across cohort contexts.

To assess the potential moderating role of PA and the mediating role of SP underlying the association between SES and cognition, we conducted a population-based, cross-national cohort study using harmonised longitudinal data from 15 countries across the USA, the UK, Europe, and China. Our objectives were threefold: first, to quantify the association between a composite measure of SES and cognitive status; second, to test whether physical activity modifies the SES-cognition association across regions; and third, to assess the extent to which social participation mediates socioeconomic differences in cognition. By integrating longitudinal evidence across distinct contexts, this study compares the patterns through which social stratification is associated with cognitive ageing across contexts.

Methods

Study design and participants

This population-based, cross-national cohort study utilised harmonised longitudinal data from four ageing surveys: the Health and Retirement Study (HRS; United States), the English Longitudinal Study of Ageing (ELSA; United Kingdom), the Survey of Health, Ageing and Retirement in Europe (SHARE), and the China Health and Retirement Longitudinal Study (CHARLS). Although CHARLS differs from Western cohorts in institutional and socioeconomic context, it follows the HRS-family design and supports a test of whether patterns extend to a major non-Western ageing context. These four datasets were purposefully selected as they are designed as “sister studies” that follow the HRS-style harmonised framework, supporting cross-cohort comparison of assessment protocols. Specifically, studies were included based on the following pre-defined criteria: (1) use of a nationally representative, longitudinal sampling design; (2) availability of harmonised socioeconomic indicators and validated cognitive assessments (Mini-Mental State Examination; MMSE) across multiple waves; and (3) presence of comparable measures for both physical activity and social participation.

To ensure consistency in observation windows, analyses were restricted to overlapping study periods: Jan 2010–Sep 2022 for HRS (waves 10–16), May 2012–Aug 2022 for ELSA (waves 6–10), Jan 2010–Dec 2022 for SHARE (waves 4–9), and Jun 2011–Aug 2020 for CHARLS (waves 1–5). Eligible participants were aged 50 years or older at baseline. We excluded individuals who were lost to follow-up, as well as those with missing baseline data on key exposures or covariates. The overlapping observation periods were selected to

support cross-cohort comparisons. The complete-case restriction was used to define the analytic sample for the mediation and moderation analyses. Potential selection biases are documented through comparisons of included and excluded participants and considered as a study limitation. The final analytic sample comprised participants with valid data across the study variables during the included observation window. After applying these criteria, 5085 individuals from HRS, 4085 from ELSA, 11451 from SHARE, and 3808 from CHARLS were included (Total N = 24429). A detailed sample selection process is presented in Additional file 1 (Figures S1–S4).

Key measures

Consistent with prior research, SES was operationalised using three key indicators, including family income, household assets, and educational attainment. Information on family income and assets was collected from the designated financial respondent within each household and treated as continuous variables. Occupational status was excluded from the present study for two primary reasons. First, there is substantial cross-national variation in occupational prestige and labour market structures between Western and Eastern contexts, which complicates the harmonisation of a single, meaningful occupational scale. Second, educational attainment, which has consistently served as a stable proxy for early-life SES and a strong determinant of later-life occupational complexity, was already included, capturing the primary cognitive-stimulating aspects of socioeconomic position. In addition, specific to the CHARLS dataset, employment is categorised predominantly into broad agricultural or non-agricultural work with a high proportion of missing values, which would have compromised the statistical power and robustness of our cross-national comparisons.

To ensure strictly positive values for log-transformation, income and asset variables were first shifted by adding the absolute value of their respective minimums plus a constant of one, followed by the application of the natural logarithm to minimise the influence of skewed distributions, a common approach in cross-national studies of SES. Educational attainment was classified into three categories, less than upper secondary, upper secondary, and tertiary, following the 2011 International Standard Classification of Education. To derive a composite SES index, we applied principal component analysis (PCA) incorporating all three indicators. PCA has been widely used to capture latent constructs such as SES by reducing multidimensional socioeconomic information into a single continuous score that retains maximum variance [15].

The primary outcome was cognitive status, assessed across all surveys using the Mini-Mental State Examination (MMSE), a widely validated tool for evaluating global cognitive function [16]. MMSE scores range from 0 to 30, with higher scores indicating better cognitive performance. The instrument captures multiple domains, including orientation to time and place, immediate and delayed recall, attention, and calculation. Its concise yet comprehensive structure makes it particularly suitable for repeated administration and for monitoring changes in cognitive performance among older adults [17]. To ensure cross-cohort comparability, we harmonised the cognitive assessments across the four databases to align with this standard 30-point scale.

PA was assessed based on the frequency of participation in vigorous and moderate activities, with mild activities also assessed in CHARLS, HRS, and ELSA. To ensure cross-cohort comparability, we harmonised the disparate measures from the four surveys. In CHARLS, original responses (yes/no) were used directly. In HRS, ELSA, and SHARE, original frequency scales were recoded into binary categories (1 = at least once a week; 0 = less than once a week), consistent with established harmonisation protocols [18]. The available binary indicators were then summed to create a physical activity index ranging from 0 to 2 in SHARE and from 0 to 3 in CHARLS, HRS, and ELSA, representing the breadth of activity intensities an individual regularly engages in. Detailed harmonisation procedures and the original survey items are presented in Additional file 1 (Table S6).

SP was measured as the number of different types of social groups or organisations in which respondents engaged. Definitions and activity lists were harmonised across surveys to ensure comparability. Examples included voluntary or charity work, attendance at educational or training courses, membership in sports or leisure clubs, and participation in community, religious, or political organisations. Responses were standardised within each survey before pooling, consistent with prior methodological frameworks on social integration and health in ageing populations.

Covariates

In line with previous research, a range of demographic, lifestyle, mental health, and physical health characteristics were included as covariates. Demographic characteristics comprised age, gender, and marital status (coded as married vs single). Lifestyle factors included smoking and alcohol consumption, each coded as binary variables (yes vs no).

Depressive symptoms were assessed using validated instruments across surveys: the eight-item Center for Epidemiological Studies Depression Scale (CES-D) in HRS and ELSA; the ten-item CES-D in CHARLS; and the 12-item EURO-D in SHARE [19]. Despite differences in format, the EURO-D and eight-item CES-D scales are strongly correlated, although agreement between the scales is moderate and cross-national comparisons require caution [20]. Both the eight-item and ten-item CES-D have been widely applied in ageing research and validated against the original 20-item version in older populations.

Functional limitations were measured using harmonised scales for activities of daily living (ADL) and instrumental activities of daily living (IADL), which capture difficulties in basic and instrumental self-care tasks. Chronic disease burden was calculated as the sum of self-reported physician-diagnosed conditions, including but not limited to high blood cholesterol, stroke, diabetes, and lung disease, consistent with established multimorbidity measures. Mobility was assessed using a composite score derived from reported limitations in functional tasks such as walking, sitting, and stooping, following prior approaches in gerontological research. Finally, self-rated health was measured by the standard global health item: “Would you say your health is excellent, very good, good, fair, or poor?”, with responses ranging from 1 to 5, where higher scores indicated poorer health. This widely used measure is a robust predictor of morbidity and mortality in older adults.

Statistical analysis

Baseline characteristics were summarised as means with standard deviations (SD) for continuous variables and frequencies with percentages for categorical variables. SES was operationalised as a standardised composite index derived through principal component analysis of educational attainment and log-transformed household income and assets. We examined effect modification by physical activity and mediation through social participation in separate prespecified analyses. To assess effect modification, we fitted linear mixed-effects models with individual-level random intercepts:

$$\text{Cognition}_{it} = \beta_0 + \beta_1 SES_{it} + \beta_2 PA_{it} + \beta_3 (SES_{it} \times PA_{it}) + \gamma^{\mathrm{T}} \mathbf{X}_{it} + u_i + \epsilon_{it}.$$

Here, $\mathbf{X}_{it}$ denotes the vector of time-varying and time-invariant covariates, u_i denotes the individual-level random intercept, and ϵ_{it} denotes the residual error. The coefficient β_3 represents effect modification of the SES-cognition association by physical activity. We used the Johnson-Neyman procedure to identify values of physical activity at which the conditional association between SES and cognition, $\beta_1 + \beta_3 PA_{it}$, was statistically distinguishable from zero.

To examine social participation as a potential mediator, we fitted a mediator model:

$$SP_{it} = \alpha_0 + aSES_{it} + \delta^{\mathrm{T}} \mathbf{X}_{it} + v_i + \eta_{it},$$

and a corresponding outcome model:

$$\text{Cognition}_{it} = \theta_0 + c' SES_{it} + bSP_{it} + \kappa^{\mathrm{T}} \mathbf{X}_{it} + w_i + \zeta_{it}.$$

Counterfactual mediation analysis was then used to estimate the average indirect association through social participation, the average direct association, the total association, and the proportion mediated. Confidence intervals were obtained using non-parametric bootstrapping with 5000 replications. Because the study was observational, mediation estimates were interpreted as statistical indirect associations rather than definitive causal effects.

As an exploratory check on longitudinal, time-ordered interdependencies among all key constructs, cross-lagged panel network (CLPN) analysis was conducted within each cohort; detailed algorithmic specifications, including nodewise regularised regression (least absolute shrinkage and selection operator; LASSO) and multiple imputation protocols, are provided in Additional file 1. To synthesise findings globally, cohort-specific estimates were pooled using random-effects meta-analysis (restricted maximum likelihood). Robustness was examined by re-estimating models on a pooled, harmonised dataset. Analyses were performed using R (version 4.1.2), with significance defined as two-sided $p < 0.05$.

Results

Baseline characteristics

The analytic sample included 24,429 participants: 5085 from HRS, 4085 from ELSA, 11451 from SHARE, and 3808 from CHARLS. As shown in Table 1, the mean age was 64.31 years (SD 7.87); 58.99% were women and 73.8% were married or partnered. Regarding education, 34.21% had less than upper secondary schooling, 43.87% had upper secondary, and 21.92% had tertiary education. At baseline, 13.25% of respondents were current smokers and 55.97% reported alcohol consumption. The largest subsamples were from the USA (20.82%), the UK (16.72%), and China (15.59%).

Table 1
Baseline characteristics of participants from four cohort studies (*N* = 24429)

Variables		**N/Mean**	**(%)/SD**	**Test**	***p*-value**
Gender	Female	14411	58.99%	-4.7253	$p < 0.0001$
	Male	10018	41.01%		
Marital Status	Married or partnered	18029	73.80%	1.8047	$p = 0.071$
	Single	6400	26.20%		
Education	Less than upper secondary	8358	34.21%	744.59	$p < 0.0001$
	Upper secondary	10717	43.87%		
	Tertiary	5354	21.92%		
Smoke	Yes	3238	13.25%	2.5527	$p = 0.011$
	No	21191	86.75%		
Drink	Yes	13674	55.97%	-14.8923	$p < 0.0001$
	No	10755	44.03%		
Country	Austria	865	3.54%	987.0689	$p < 0.0001$
	Belgium	1005	4.11%		
	China	3808	15.59%		
	Czech Republic	1176	4.81%		
	Denmark	723	2.96%		
	Estonia	1769	7.24%		
	France	1284	5.26%		
	Germany	487	1.99%		
	Italy	816	3.34%		
	Slovenia	742	3.04%		
	Spain	731	2.99%		
	Sweden	614	2.51%		
	Switzerland	1239	5.07%		
	UK	4085	16.72%		
	USA	5085	20.82%		
Age		64.31	7.87	-0.1449	$p < 0.0001$
Asset		0	1	0.094	$p < 0.0001$
Income		0	1	0.242	$p < 0.0001$
ADL		1.13	2.39	-0.3097	$p < 0.0001$
IADL		1.03	2.23	-0.328	$p < 0.0001$
Self-rated health		2.92	1.07	-0.2366	$p < 0.0001$

Notes: Values in the "Test" column represent the following statistical analyses regarding their association with cognitive status: t-statistics from independent samples t-tests for binary variables; F-statistics from one-way ANOVA for categorical variables with three or more levels; and Pearson's correlation coefficients (r) for continuous variables. $p < 0.05$ was considered statistically significant. To ensure cross-national comparability, income and assets were log-transformed and standardised (Z-score) within each country-specific cohort prior to analysis. Original data were collected in USD (HRS), GBP (ELSA), EUR (SHARE), and CNY (CHARLS).

Variables	N/Mean	(%)/SD	Test	*p*-value
Depression	4.9	7.07	-0.3162	$p < 0.0001$
Chronic disease	1.32	1.29	-0.0964	$p < 0.0001$
Physical activity	1.58	0.93	0.1994	$p < 0.0001$
Mobility	2.94	4.46	-0.3455	$p < 0.0001$
Socioeconomic status	0.13	0.98	0.274	$p < 0.0001$
Social participation	1.71	1.59	0.2802	$p < 0.0001$
Cognitive status	15.85	4.84		

Notes: Values in the "Test" column represent the following statistical analyses regarding their association with cognitive status: t-statistics from independent samples t-tests for binary variables; F-statistics from one-way ANOVA for categorical variables with three or more levels; and Pearson's correlation coefficients (*r*) for continuous variables. $p < 0.05$ was considered statistically significant. To ensure cross-national comparability, income and assets were log-transformed and standardised (Z-score) within each country-specific cohort prior to analysis. Original data were collected in USD (HRS), GBP (ELSA), EUR (SHARE), and CNY (CHARLS).

Mean baseline values (SD) of key variables were as follows: the mean values for standardised household assets and standardised household income were both 0 (SD = 1), ADL limitations 1.13 (2.39), IADL limitations 1.03 (2.23), self-rated health 2.92 (1.07), depressive symptoms 4.90 (7.07), number of chronic conditions 1.32 (1.29), physical activity 1.58 (0.93), mobility limitations 2.94 (4.46), SES index 0.13 (0.98), social participation 1.71 (1.59), and cognitive status 15.85 (4.84).

In bivariate analyses, cognitive function varied significantly by gender, education, smoking and drinking status, and country, but not by marital status ($p = 0.071$). Pearson's correlations showed positive associations of cognition with income, assets, SES, physical activity, and social participation, and negative associations with age, depressive symptoms, mobility limitations, ADL and IADL limitations, self-rated health, and chronic conditions (all $p < 0.0001$). Cohort-specific baseline characteristics are detailed in Additional file 1 (Tables S8–S11).

[Table 1 near here]

Association between SES and cognition

In linear mixed-effects models with individual random intercepts and cluster-robust standard errors, higher SES was consistently associated with better cognitive function across all four cohorts. Random-effects meta-analysis of cohort-specific estimates yielded a pooled effect of SES on cognition (β = 0.96, 95% CI = 0.17–1.75), with positive associations in each survey: ELSA (β = 0.46, 95% CI = 0.40–0.53), HRS (β = 0.88, 95% CI = 0.82–0.93), SHARE (β = 0.38, 95% CI = 0.32–0.43), and CHARLS (β = 2.12, 95% CI = 1.99–2.25). Physical activity was positively related to cognition in the pooled analysis (β = 0.191, 95% CI = 0.05–0.33), with significant associations in ELSA, HRS, and SHARE but not in CHARLS. Social participation also demonstrated an independent contribution to cognition (β = 0.394, 95% CI = 0.18–0.61).

Figure 1 presents the cohort-specific cross-lagged panel networks. Across the four cohorts, SES and social participation were among the most consistently retained predictors of cognitive function at the subsequent wave, with recurrent positive edges from SES to social participation and from social participation to cognition. Cross-lagged associations involving physical activity were less consistent, and associations among depressive symptoms, chronic conditions, self-rated health, mobility, and functional limitations varied across cohorts. These exploratory findings indicate a recurring time-ordered pattern linking socioeconomic circumstances, social participation, and subsequent cognitive function, but should not be interpreted as evidence of a causal pathway.

Moderating role of physical activity

Evidence of moderation by physical activity was observed, though the direction and magnitude varied by cohort. As shown in Table 2, in HRS (β = 0.17, 95% CI = 0.13–0.22) and CHARLS (β = 0.155, 95% CI = 0.06–0.25), higher physical activity amplified the positive SES–cognition association. By contrast, in SHARE (β = − 0.11, 95% CI = − 0.16 to − 0.05), physical activity attenuated this association, and in ELSA (β = − 0.023, 95% CI = − 0.07 to 0.02) no significant effect was detected. Stratified analyses within SHARE consistently showed negative or null interaction effects across countries. To further probe this heterogeneity beyond traditional simple slope analyses, we

applied the Johnson–Neyman technique [21]. Rather than evaluating conditional associations only at selected values, the Johnson–Neyman approach identifies the range of physical activity over which the conditional SES–cognition association is statistically distinguishable from zero [21]. As illustrated in Fig. 2, in HRS and CHARLS, the cognitive returns of higher SES strengthened progressively with greater physical activity, whereas in SHARE the socioeconomic gradient in cognition weakened as activity levels increased. ELSA showed a downward point-estimate trend, but its interaction was not statistically significant.

Table 2
Results of linear mixed-effects models

	ELSA		HRS		SHARE		CHARLS		Meta Analysis		
	Coef.	**C-SE**	**Coef.**	**C-SE**	**Coef.**	**C-SE**	**Coef.**	**C-SE**	**Coef.**	**SE**	I^2
Intercept	113.901	18.228	458.06	17.98	-729.28	10.200	-1110	43.776	-316	373	99.9
Gender	0.972***	0.078	0.93***	0.10	0.930***	0.060	-1.130***	0.139	0.431	0.515	99.3
Age	-0.138***	0.006	0.01**	0.01	-0.160***	0.004	-0.088***	0.007	-0.093*	0.037	99.5
Marital Status	-0.198**	0.078	0.07	0.08	0.050***	0.010	-0.082*	0.046	-0.034	0.059	84.7
Smoke	-0.262**	0.123	0.23*	0.11	-0.650***	0.060	-0.266*	0.160	-0.242	0.188	92.0
Self-rated health	-0.169***	0.030	-0.36***	0.04	-0.150***	0.020	-0.173***	0.052	-0.211***	0.05	89.5
Mobility	0.051***	0.017	-0.05**	0.02	-0.050***	0.010	-0.071***	0.014	-0.03	0.027	93.0
ADL	-0.005	0.043	-0.10*	0.05	0.030	0.030	0.153***	0.050	0.019	0.051	84.1
IADL	-0.411***	0.051	-1.16***	0.06	-0.440***	0.020	-0.337***	0.032	-0.584***	0.19	99.3
Drink	0.364***	0.056	0.06	0.08	0.460***	0.040	-0.186	0.119	0.189	0.143	95.4
Chronic disease	-0.062**	0.024	0.25***	0.03	0.050***	0.010	0.176***	0.041	0.099	0.069	96.9
Depression	0.044*	0.025	-0.10	0.10	-0.140***	0.009	-0.046***	0.010	-0.057	0.046	97.2
Time	-0.045***	0.009	-0.22***	0.01	0.380***	0.005	0.563***	0.022	0.168	0.181	99.9
SES	0.463***	0.034	0.88***	0.03	0.380***	0.030	2.120***	0.063	0.96*	0.401	99.8
Social participation	0.118***	0.025	0.35***	0.01	0.490***	0.010	0.626***	0.049	0.394***	0.108	99.2
Physical activity	0.181***	0.035	0.37***	0.03	0.200***	0.030	0.006	0.047	0.191**	0.073	94.6
SES*Physical activity	-0.023	0.028	0.17***	0.02	-0.110***	0.030	0.155***	0.044	0.048	0.068	95.7

Notes: C-SE = Cluster-robust SE; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

[Table 2 near here]

Mediating role of social participation

As shown in Table 3 and Fig. 3, the estimated indirect association between SES and cognitive status through social participation was positive in all four cohorts: ELSA (β = 0.012, 95% CI 0.0071–0.020), HRS (β = 0.044, 95% CI 0.038–0.051), SHARE (β = 0.155, 95% CI 0.145–0.170), and CHARLS (β = 0.164, 95% CI 0.136–0.190). Because the data are observational, these estimates are interpreted as indirect associations rather than definitive causal mediation effects.

Table 3
Results of mediation analysis

Cohort and effect	Estimate	95% CI Lower	95% CI Upper	*p*-value
ELSA				
Indirect effects	0.012	0.007	0.020	$p < 0.0001$
Direct effects	0.463	0.401	0.520	$p < 0.0001$
Total effects	0.475	0.415	0.530	$p < 0.0001$
Prop. Mediated	0.025	0.014	0.040	$p < 0.0001$
HRS				
Indirect effects	0.044	0.038	0.051	$p < 0.001$
Direct effects	0.884	0.826	0.940	$p < 0.001$
Total effects	0.928	0.872	0.983	$p < 0.001$
Prop. Mediated	0.047	0.040	0.056	$p < 0.001$
SHARE				
Indirect effects	0.155	0.145	0.170	$p < 0.0001$
Direct effects	0.378	0.322	0.430	$p < 0.0001$
Total effects	0.534	0.479	0.590	$p < 0.0001$
Prop. Mediated	0.291	0.259	0.330	$p < 0.0001$
CHARLS				
Indirect effects	0.164	0.136	0.190	$p < 0.0001$
Direct effects	2.124	2.004	2.240	$p < 0.0001$
Total effects	2.288	2.166	2.410	$p < 0.0001$
Prop. Mediated	0.072	0.059	0.090	$p < 0.0001$
Meta Analysis				
Indirect effects	0.093	0.033	0.152	$p = 0.002$
Direct effects	0.959	0.429	1.489	$p < 0.0001$
Total effects	1.053	0.526	1.579	$p < 0.0001$
Prop. Mediated	0.102	0.043	0.161	$p < 0.0001$

As a robustness check, we re-estimated the models using a harmonised dataset generated by appending all four cohorts. Positive SES–cognition and social participation–cognition associations were also observed in the pooled analyses. However, the SES–physical activity interaction differed between the pooled model specifications (Additional file 1, Tables S20 and S24), and should not be interpreted as uniformly present.

[Table 3 near here]

Discussion

This longitudinal, multi-cohort study spanning 15 countries systematically compares the distinct roles of physical activity (PA) and social participation (SP) in the SES–cognition relationship across the USA, Europe, and China. Higher SES was consistently associated with better cognitive function, aligned with cumulative advantage and cognitive reserve frameworks [3, 22]. By integrating these health behaviours into a unified, harmonised analytical framework, we identified divergent moderating patterns of PA across cohorts, whereas SP operated as a consistent potential pathway linking SES to cognitive maintenance.

Our findings may help reconcile long-standing empirical contradictions regarding whether PA narrows or widens health disparities. We identified a “resource amplification” pattern in the USA and China, where PA accentuates the cognitive advantages of higher SES, potentially functioning as a commodity that compounds existing privilege [23, 24]. One possible contextual explanation is that, in stratified societies with higher income inequality or less comprehensive welfare padding, high-SES individuals possess greater material and social capital to access structurally sustained, cognitively stimulating leisure-time exercises (e.g., organised sports or supervised training) [24]. In the US and China, physical activity among lower-SES groups may be heavily patterned by high-strain, occupational labour that may offer different opportunities for cognitive stimulation than leisure-time activity. Conversely, the “health equalisation” pattern observed in continental Europe suggests that robust social safety nets, integrated healthcare, and egalitarian urban infrastructures [25] (e.g., subsidised transit and barrier-free walking designs) may convert active lifestyles into a more widely accessible public good, thereby narrowing the cognitive gradient for socioeconomically disadvantaged older adults [26]. These contextual explanations were not directly tested in the present analyses.

In contrast to the context-dependent nature of PA, the indirect association of SES with cognition through SP was positive across all cohorts. Two complementary frameworks help explain this consistency. The Cognitive Reserve Hypothesis posits that social engagement enriches cognitive stimulation, strengthening neural networks and delaying cognitive decline [4, 27]. Meanwhile, the Stress-Buffering Hypothesis emphasises how social networks mitigate the deleterious effects of chronic stress, particularly salient among lower-SES groups [28, 29]. The cognitive returns of social integration may therefore involve persistent cognitive stimulation [30], stress-buffering neuroprotection, and mutual emotional support [31]. Together, these mechanisms suggest social participation as a consistent potential pathway linking SES to cognitive health [32].

Our findings challenge a “one-size-fits-all” approach to reducing cognitive inequalities. Physical-activity promotion should incorporate explicit equity targets to reduce the risk that interventions inadvertently widen cognitive disparities by favouring resource-rich groups. Expanding the social infrastructure for later-life engagement (e.g., accessible volunteering networks and community-integrated peer groups) represents a potential strategy to promote cognitive health in later life. Because individual behaviour is structurally patterned, these lifestyle modifications should be paired with equity-oriented policies addressing life-course structural disadvantages, such as income insecurity and unequal healthcare access.

Several limitations merit consideration. First, as an observational study, residual confounding from unmeasured genetic or nutritional variables cannot be entirely eliminated, and potential reverse causality remains a challenge. Second, while the MMSE is widely validated, it is susceptible to ceiling effects; future cross-national replications should utilise comprehensive neuropsychological batteries to track domain-specific cognitive trajectories. Third, lifestyle factors were self-reported, which may introduce recall or social desirability biases. Fourth, due to severe cross-national institutional heterogeneity and localised missing data (particularly within rural agricultural sectors in CHARLS), occupational status was excluded from our SES composite, which might overlook specific workplace-related cognitive stimuli. Finally, our analytical sample was restricted to complete-case participants within the overlapping observation window. This restriction may introduce selection bias toward healthier survivors, potentially underestimating the magnitude of the observed social gradients in more vulnerable strata.

Conclusions

Across four longitudinal ageing cohorts covering 15 countries, higher SES was consistently associated with better cognitive function. Social participation showed a positive indirect association with this relationship in each cohort, while the interaction between SES and PA differed in direction and statistical significance across cohorts. These findings underscore the value of examining both social pathways and context-specific patterns when developing research and policy responses to socioeconomic inequalities in cognitive ageing.

Abbreviations

ADL
activities of daily living
ANOVA
analysis of variance
CES-D
Center for Epidemiological Studies Depression Scale
CHARLS

China Health and Retirement Longitudinal Study
CI
confidence interval
CLPN
cross-lagged panel network
C-SE
cluster-robust standard error
ELSA
English Longitudinal Study of Ageing
HRS
Health and Retirement Study
IADL
instrumental activities of daily living
LASSO
least absolute shrinkage and selection operator
MMSE
Mini-Mental State Examination
PA
physical activity
PCA
principal component analysis
SD
standard deviation
SE
standard error
SES
socioeconomic status
SHARE
Survey of Health,Ageing and Retirement in Europe
SP
social participation.

Declarations

Ethics approval and consent to participate

All analyses were conducted using de-identified, publicly available data, and informed consent was obtained from all participants in each original cohort. The present secondary analysis was conducted in accordance with the ethical principles of the Declaration of Helsinki. Ethical approval was obtained for each original survey by their respective institutional review boards. Specifically, HRS was approved by the Institutional Review Board of the University of Michigan; ELSA was approved by the National Research Ethics Service (NRES) Committee South Central - Berkshire (with wave-specific approval numbers including 11/SC/0374 for Wave 6, 13/SC/0532 for Wave 7, 15/SC/0526 for Wave 8, 17/SC/0588 for Wave 9, and 21/SC/0030 for Wave 10); SHARE (Waves 4–9) was reviewed and approved by the Ethics Council of the Max Planck Society; and CHARLS was approved by the Biomedical Ethics Committee of Peking University (Approval No. IRB00001052-11015). No additional ethical approval was required for this secondary analysis.

Consent for publication

Not applicable.

Availability of data and materials

Data used for this study are publicly available from the original surveys to registered users. Source data can be accessed through the HRS Data Portal, ELSA data access page, SHARE Data Hub, and CHARLS website, subject to the respective data providers' registration and access requirements.

Competing interests

The authors declare no competing interests.

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Authors' contributions

BF: Conceptualization, Supervision, Writing – review & editing. YW: Methodology, Formal analysis, Visualization, Writing – original draft. TF: Writing – review & editing. XQ: Writing – review & editing. EY: Conceptualization, Supervision, Writing – review & editing. All authors approved the manuscript for submission.

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Figures

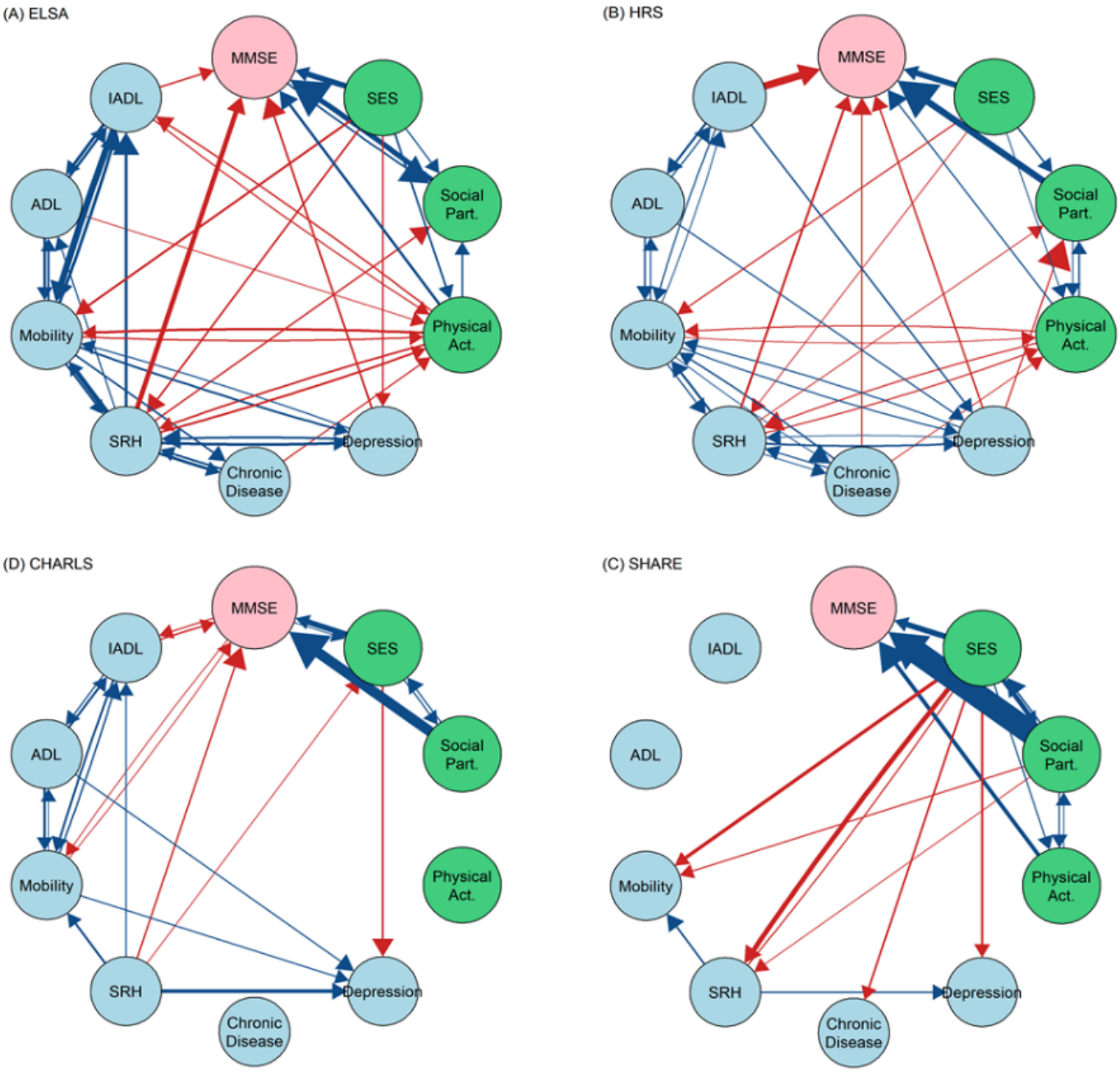


Figure 1

Network structures across four cohorts

Notes: Panels show cohort-specific directed temporal networks for (A) ELSA, (B) HRS, (C) SHARE, and (D) CHARLS. Nodes represent cognitive function (MMSE), exposures (SES, social participation, physical activity), and health/function indicators (depressive symptoms, chronic disease burden, self-rated health, mobility, ADL, and IADL). Directed edges indicate cross-lagged associations from time t to time t+1 estimated via nodewise regularised regression (LASSO) with cross-validated penalty selection. Edge thickness is proportional to the magnitude of the regularised regression coefficient (edge weight). Blue edges denote positive temporal associations and red edges denote negative temporal associations. The cross-lagged coefficient was shrunk to zero by LASSO regularisation (i.e., it was not sufficiently stable or informative after conditioning on the other variables).

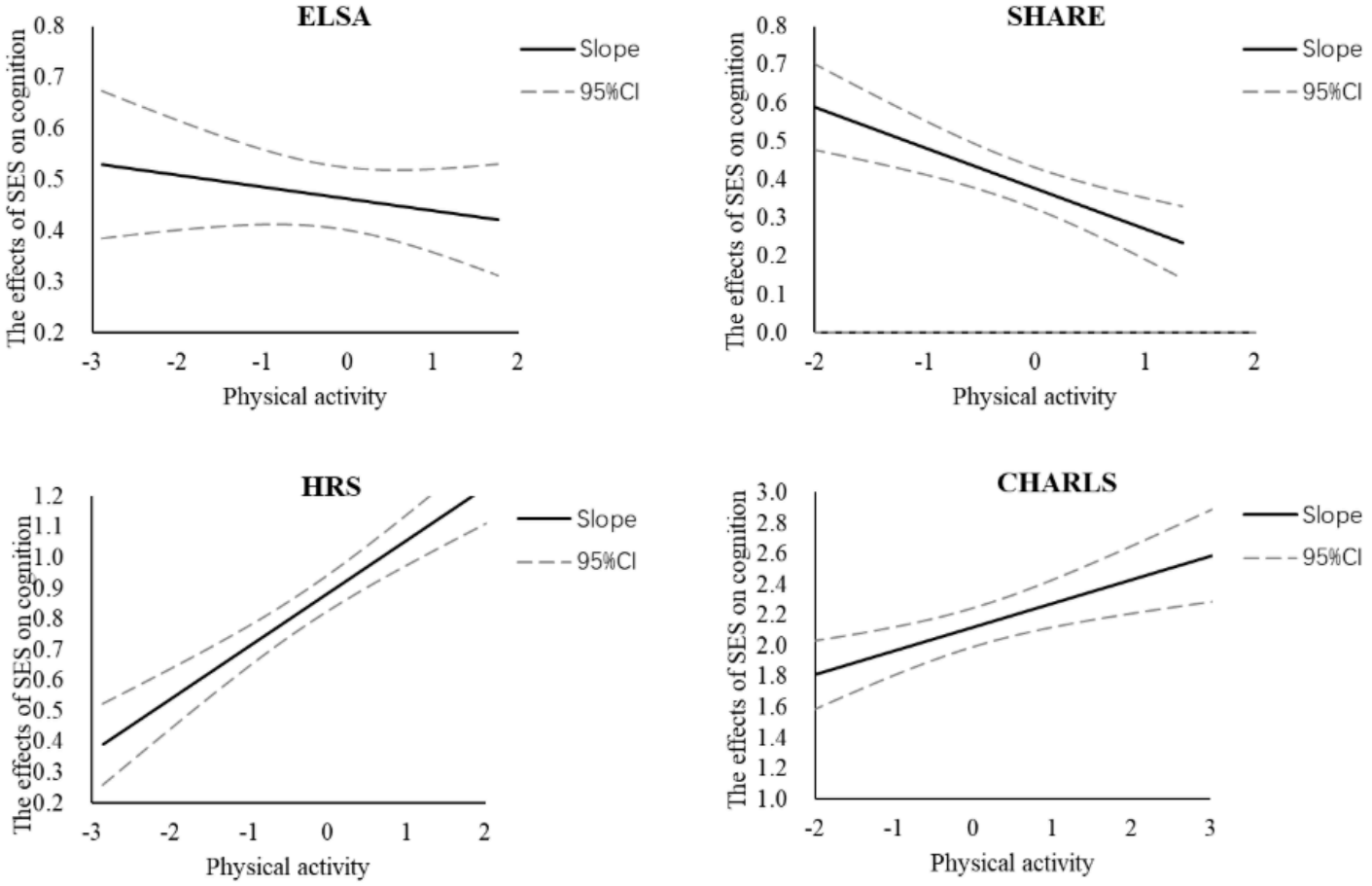


Figure 2

Diagram of the Johnson–Neyman analysis.

Notes: Solid lines show the estimated conditional association between socioeconomic status (SES) and cognition across physical activity levels; dashed lines indicate 95% confidence intervals. Panels show ELSA (upper left), SHARE (upper right), HRS (lower left), and CHARLS (lower right).

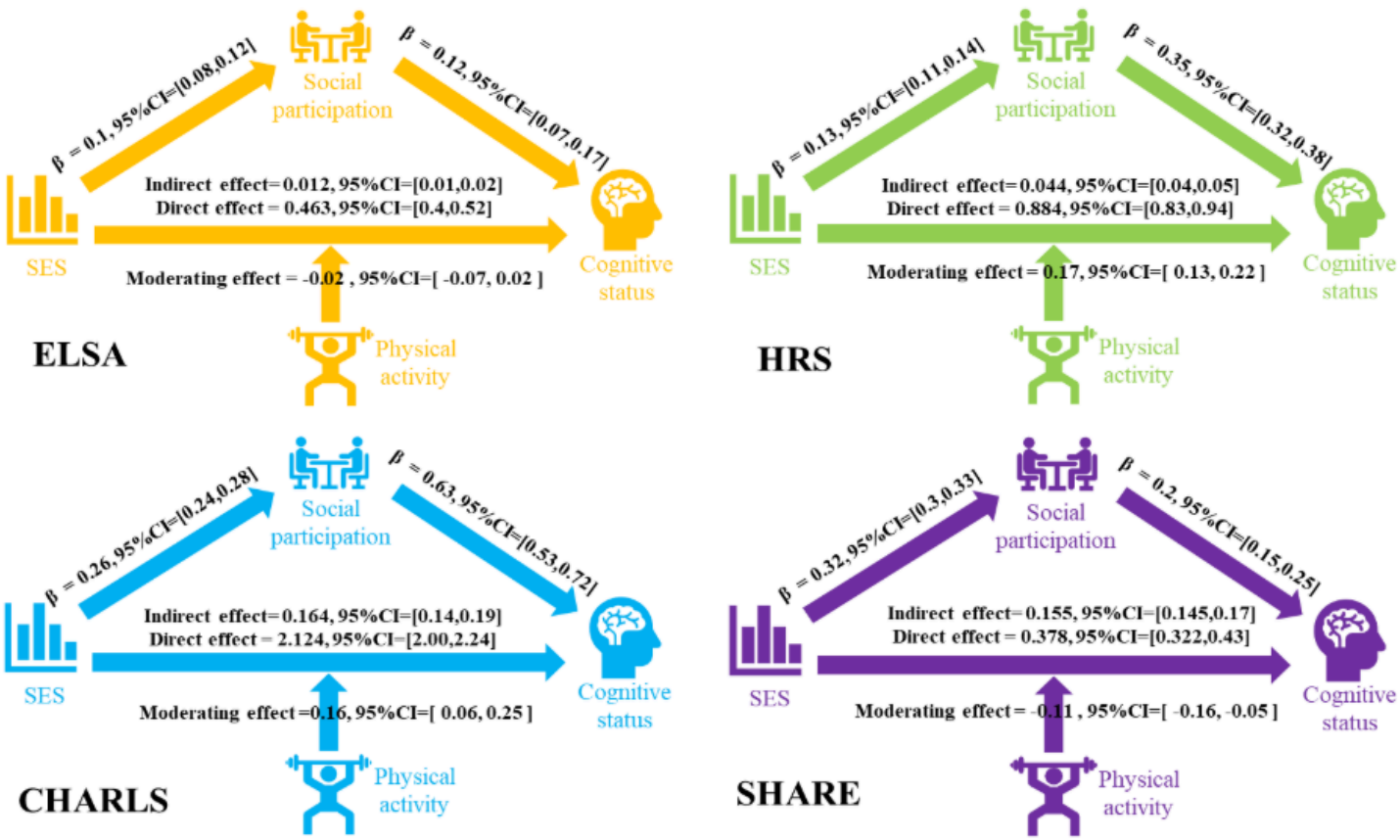


Figure 3

Diagram of the mediation and moderation analyses.

Notes: Panels show cohort-specific estimates of indirect associations through social participation and effect modification by physical activity. Arrow labels report regression coefficients (β) and 95% confidence intervals (CI). Direct associations, indirect associations, and the SES–physical activity interaction are displayed. SES, socioeconomic status. Estimates are observational associations.

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