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Educational inequalities in the onset of functional limitations and verbal memory decline in the United States and Europe: A longitudinal perspective

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Abstract

Background: Educational attainment is a well-established social determinant of health in later life, yet longitudinal cross-national comparisons of its relationship with the onset of functional disability and verbal memory decline remain scarce.

Objective: To examine the association between education and the onset of functional disability (ADL and IADL limitations) and verbal memory decline among adults aged 50 and older across the United States and four European regions.

Methods: We used harmonized longitudinal data from the HRS (2012-2022) in the United States and SHARE (2013-2022) in Europe. Starting from a disability-free baseline, we constructed nested and logistic regression models with inverse probability weights to estimate the association between educational attainment and ADL, IADL, and verbal recall outcomes.

Results: Among 68,719 participants (14,871 US; 53,848 Europe), highly educated Americans had higher predicted IADL disability probabilities (females: 4.2%; males: 2.9%) than those with low education in all European regions for women, and all but Eastern Europe for men. Low education was significantly associated with ADL and IADL disability onset across most regions, with the strongest IADL gradients in Eastern Europe (OR 3.10, 95% CI 2.09-4.74 for females) and the US (OR 2.29, 95% CI 1.79-2.93 for males). Education was not significantly associated with verbal memory decline in any region or sex.

Conclusions: Educational inequalities in late-life functional disability were strongest and most persistent in the US and Eastern Europe, with highly educated Americans facing higher predicted IADL disability risk than the least educated adults across most European regions.

Keywords: ADL, IADL, aging, cross-national comparison, HRS, SHARE, inverse probability weighting, physical limitations, quality of life, morbidity

Introduction

Population aging is one of the defining challenges of this century. By 2050, the share of the global population aged 60 and older is projected to nearly double, from 12% to 22%, placing growing demands on health and social care systems worldwide (World Health Organization, 2025). Within this trajectory, functional and cognitive disability are among the most consequential outcomes, shaping quality of life, healthcare utilization, and long-term care costs (Callaway et al., 2025).

Socioeconomic inequalities in late-life health are substantial and persistent across high-income countries. Educational attainment as a proxy for socioeconomic status, is one of the strongest and most consistent predictors of health outcomes in later life (Arpino & Solé-Auró, 2019; Rubio Valverde, Mackenbach, Bopp, et al., 2021; Rubio Valverde, Mackenbach, & Nusselder, 2021; Stolz et al., 2025). Higher education is associated with healthier behaviors, better jobs, higher incomes, and greater access to healthcare, all of which reduce the risk of functional decline (Cutler & Lleras-Muney, 2010; Zajacova & Lawrence, 2018) through a range of mechanisms, as the theory of fundamental causes of disease posits (Link & Phelan, 1995).

Limitations in activities of daily living (ADLs) and instrumental activities of daily living (IADLs) are widely used standard measures of functional disability in population-based research (Katz, 1963, 1983; Lawton & Brody, 1969). ADLs assess basic self-care tasks such as bathing and dressing, while IADLs measure more complex activities required for independent living, such as managing finances and medications. These measures are commonly applied within the disablement process framework (Verbrugge & Jette, 1994), which explains how chronic conditions, injuries, and impairments lead to functional limitations that reduce quality of life and restrict the ability to carry out everyday activities (Verbrugge et al., 1989; Zajacova & Margolis, 2025).

Cross-national comparisons of functional disability in later life have consistently documented a US health disadvantage relative to Europe. Using harmonized data from HRS, ELSA, and SHARE across 15 countries, Wahrendorf et al. (2013) found that disability levels were highest in the United States, lower in Eastern and Southern Europe, and lowest in Northern and Western Europe, concluding that weaker social policies and greater socioeconomic inequality were associated with both higher disability burden and earlier onset. Similarly, Kekäläinen et al. (2023), in an incident-disability design using HRS and SHARE across 19 countries, showed that physical and cognitive functional capacity predicted ADL and IADL onset consistently across Western countries, though associations were attenuated in settings with higher GDP and broader health coverage.

Within Europe, educational inequalities in functional health have been documented across multiple contexts. Studies using SHARE have found that lower-educated individuals face larger absolute gaps in disability-free life expectancy in Eastern Europe, with women in Central and Eastern European countries experiencing particularly pronounced inequalities (Stonkute et al., 2023). Complementary analyses across 15 European countries have identified low income, excess body weight, and smoking as the primary mediators of educational inequalities in disability-free life expectancy, with Eastern Europe again showing the greatest potential for reduction (Rubio Valverde, Mackenbach, Bopp, et al., 2021). Comparing the US and England, a multistate life table study using data from HRS and ELSA found socioeconomic inequalities in disability-free life expectancy to be broadly similar in England and the United States, with wealth exhibiting the largest absolute gradient (Zaninotto et al., 2020). Looking beyond a single time point, Wilkie et al. (2024) found that educational inequalities in functional limitations widened over time in several high- and middle-income countries, driven by rising limitations among the least-educated in some countries, and improvements concentrated among the most-educated in others.

Beyond functional disability, educational inequalities in cognitive aging have attracted growing attention, though the mechanisms remain debated. One proposed mechanism is cognitive reserve, i.e., the idea that education builds neural resilience that allows the brain to compensate for damage or neurodegeneration more efficiently (Stern, 2002; Stern et al., 2020). The 2024 *Lancet Commission on Dementia* concluded that more years of education benefit cognitive aging (Livingston et al., 2024), consistent with this theory. However, others argue that the association between education and cognitive health may be mediated by income (Zahodne et al., 2015), and longitudinal evidence increasingly supports the notion that education predicts level, but not trajectory, of decline (Berggren et al., 2018; Dixon et al., 2004; Fjell et al., 2025; Lenehan et al., 2015).

Despite this growing evidence base, several gaps remain. Most prior cross-national studies examine disability prevalence or disability-free life expectancy using cross-sectional or Sullivan-like method approaches (Sullivan, 1971), rather than following individuals free of limitations at baseline through to disability onset. Measurement equivalence across international aging surveys also cannot be assumed; item response theory analyses have documented meaningful differential item functioning in ELSA disability items that does not affect HRS and SHARE comparisons (Chan et al., 2012), supporting the use of these two surveys as the basis for harmonized cross-national analysis. Studies comparing the US to multiple European regions simultaneously within a unified analytical framework with harmonized longitudinal data remain scarce. To our knowledge, no prior study has jointly examined ADL disability, IADL disability, and verbal memory decline using this incident design across the four major European welfare-state regions and the United States in the same analytical framework. Moreover, no prior study has done so while also quantifying the share of educational gradients explained by chronic health conditions. This study addresses these gaps using harmonized data from HRS and SHARE across five regions, with sex-stratified logistic regression models and inverse probability weighting to account for differential attrition.

In this study, we examine the association between educational attainment and onset of functional and cognitive disability among adults aged 50 and older across the United States and four regions of Europe (Nordic, Western, Mediterranean, and Eastern). Functional disability is defined as the inability to independently perform basic activities of daily living (ADL) and instrumental activities of daily living (IADL), while cognitive decline is defined as a clinically meaningful drop in verbal recall test scores. We also assess the extent to which chronic health conditions and other health characteristics mediate the education-disability relationship, and whether the strength of these associations varies across regions. Using harmonized longitudinal data from the Health and Retirement Study (HRS) and the Survey of Health, Ageing and Retirement in Europe (SHARE), we examine disability onset and verbal memory decline over follow-up periods of 10 and nine years respectively. Our study sample is adults who were free of functional limitations at baseline, which allows us to study the transition from independence to disability, rather than disability prevalence.

Methods

Data Sources

Data were drawn from two internationally harmonized longitudinal studies of aging. The HRS is a longitudinal, comprehensive, national representative survey of Americans aged 50+, established in 1992, collecting data on health, health-related behaviors, and socio-demographic factors. The National Institute on Aging (grant number NIA U01AG009740) sponsors the HRS at the University of Michigan. We used the RAND HRS longitudinal file that provides a harmonized set of variables across waves (RAND Corporation, 2022). As this study was a secondary analysis of existing deidentified publicly available data, IRB approval was not required under 45 CFR §46.101(b)(4). The study followed the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) reporting guideline (Von Elm et al., 2008). We used data from Wave 11 (2012) as our baseline through Wave 16 (2022), providing a 10-year follow-up window (Sonnega et al., 2014). SHARE is a panel study of individuals aged 50 and older across European countries, with biennial data collection since 2004. We used Wave 5 (2013) as the European baseline through Wave 9 (2022), providing a comparable nine-year follow-up (Börsch-Supan et al., 2013). Both studies are designed for cross-national comparability, with harmonized variables and standardized instruments across surveys. Data were accessed via Gateway to Global Aging Data (Lee et al., 2021).

Study Sample

The analytical sample comprised individuals aged 50 years and older at baseline who met the following inclusion criteria: 1) no reported ADL limitations and no IADL limitations; 2) complete cases on educational attainment; and 3) at least one follow-up observation. The final pooled sample comprised 68,719 participants across five regions: the United States (n = 14,871); Nordic Europe (Denmark and Sweden; n = 7,711); Western Europe (Austria, Belgium, Germany, Luxembourg, the Netherlands, and Switzerland; n = 21,060); Mediterranean Europe (France, Italy, and Spain; n = 13,322); and Eastern Europe (Czechia, Estonia, and Slovenia; n = 11,755). This regionalization is in line with other studies that analyze SHARE on the regional level according to political histories and welfare state systems (Eikemo et al., 2008).

Because individuals with lower education are more likely to already have functional limitations at first observation, restricting the sample to individuals free of limitations at baseline allowed us to examine the incidence of new disability over follow-up, providing a cleaner test of whether educational attainment protects against the transition from independence to functional limitation (Freedman et al., 2016).

Measures

ADL disability onset was defined as the development of one or more limitations in bathing, dressing, eating, toileting, or walking across a room at any follow-up wave among individuals with zero ADL limitations at baseline.

IADL disability onset was defined as the development of one or more limitations in managing money, taking medications, shopping for groceries, preparing meals, or using the telephone at any follow-up wave among individuals with zero IADL limitations at baseline.

Verbal memory decline was defined as a drop of three or more points in total word recall (sum of immediate and delayed recall, range 0-20 in HRS, 0-20 harmonized from 0-10 scales in SHARE) between baseline and the last available follow-up wave. This threshold corresponds to approximately 0.9 SD of the change score distribution (change score SD = 3.32 in SHARE; baseline SD = 3.61), representing a clinically meaningful decline in episodic memory function.

Educational attainment was classified into three categories based on the International Standard Classification of Education (ISCED): Low (ISCED 0-2: primary or lower secondary education), Medium (ISCED 3-4: upper secondary or post-secondary non-tertiary), and High (ISCED 5-6: tertiary education). High education served as the reference category in all analyses.

Covariates measured at baseline included: age (continuous, in years), self-rated health (poor/fair vs. good/very good/excellent), partnership status (married or partnered vs. not), hypertension (ever diagnosed), diabetes (ever diagnosed), obesity (BMI ≥ 30), mobility limitations at baseline (any difficulty walking, climbing stairs, or other physical mobility tasks), and current or past smoking status (ever smoker).

Statistical analysis

To take into account difference in educational attainment and age structure across regions, we estimated logistic regressions separately by region, sex, and outcome. Three model specifications were used:

- Model 1 (parsimonious): Education + age
- Model 2 (intermediate): Model 1 + self-rated health + partnership status + mobility limitations at baseline
- Model 3 (full): Model 2 + hypertension + diabetes + obesity + smoking

All models incorporated inverse probability weights (IPW) to account for differential attrition over the follow-up period. IPW were estimated from logistic regression models predicting follow-up participation as a function of baseline covariates, and were stabilized and trimmed at the 1st and 99th percentiles to reduce the influence of extreme weights.

This sequential modeling strategy allowed us to assess the degree to which sociodemographic and health factors attenuate the education-outcome association. Attenuation was calculated as the percentage reduction in the log-odds of the education coefficient between models, following the formula:

$$\text{Attenuation (\%)} = \frac{\text{OR}_{\text{Model } k} - \text{OR}_{\text{Model } k+1}}{\text{OR}_{\text{Model } k} - 1} \times 100$$

We computed predicted probabilities of each outcome from the full model under two counterfactual profiles: 1) a “healthy” profile (reference values for all covariates, representing a non-smoking, non-obese, normotensive, non-diabetic, mobile, good-health, partnered individual at mean age); and 2) an "average" profile (covariates set to observed sample means/modes). This dual-profile approach separates the education effect from comorbidity burden.

Model fit was evaluated using Nagelkerke's pseudo-R^2. All analyses were conducted in R version 4.3.1 using base regression functions.

We conducted five additional sensitivity analyses to assess the robustness of the findings, which included models with shorter follow-up windows, disaggregated cognitive components, mortality as a competing outcome, unweighted estimates, and false discovery rate (FDR) correction for multiple comparisons. The code to replicate the analysis is available at XXX.

Results

Table 1 details the baseline characteristics of the analytical sample by region. The total sample comprised 68,719 adults free from functional limitations aged 50 and older. The mean age was similar across regions (65-66 years). The US sample had the highest prevalence of chronic conditions: diabetes (20.2%), obesity (33.0%), and hypertension (56.3%). Mediterranean Europe had the highest proportion of low-educated individuals (64.5%), while the US had the lowest (17.4%). Partnership rates were notably lower in the US (67.1%) compared with European regions (87-93%). Mortality during follow-up was highest in the US (20.8%) and lowest in Western Europe (7.4%), with intermediate rates in Eastern Europe (15.0%), Nordic Europe (10.9%), and Mediterranean Europe (9.8%).

Table 1. Baseline characteristics by region (N = 68,719)

	United States	Nordic	Western	Mediterranean	Eastern
n	14,871	7,711	21,060	13,322	11,755
Age, mean (SD)	66.3 (10.1)	66.1 (9.4)	64.9 (9.4)	66.1 (9.6)	65.9 (9.0)
Female %	56.9 (56.1-57.7)	53.4 (52.3-54.5)	54.1 (53.4-54.8)	53.7 (52.9-54.6)	58.4 (57.5-59.3)
Partnered %	67.1 (66.4-67.9)	88.3 (87.5-89.1)	87.9 (87.4-88.4)	93.2 (92.8-93.7)	87.4 (86.7-88.1)
Education					
Low edu %	17.4 (16.8-18.0)	26.8 (25.8-27.8)	27.8 (27.2-28.4)	64.5 (63.7-65.3)	31.7 (30.8-32.5)
Medium edu %	56.1 (55.3-56.9)	35.9 (34.8-37.0)	43.6 (42.9-44.2)	21.9 (21.1-22.6)	49.8 (48.9-50.7)
High edu %	26.5 (25.8-27.2)	37.3 (36.2-38.4)	28.6 (28.0-29.2)	13.7 (13.1-14.2)	18.6 (17.9-19.3)
Health					
Poor SRH %	18.4 (17.8-19.0)	18.8 (18.0-19.7)	25.2 (24.6-25.7)	34.4 (33.6-35.2)	47.5 (46.6-48.4)
Hypertension %	56.3 (55.5-57.1)	39.7 (38.7-40.8)	39.8 (39.2-40.5)	42.3 (41.5-43.1)	53.4 (52.5-54.3)
Diabetes %	20.2 (19.6-20.9)	9.4 (8.7-10.0)	11.0 (10.6-11.4)	13.6 (13.1-14.2)	15.5 (14.9-16.2)
Obese %	33.0 (32.2-33.7)	14.7 (13.9-15.5)	18.7 (18.2-19.2)	17.7 (17.1-18.4)	26.7 (25.9-27.6)
Mobility limit %	38.0 (37.2-38.8)	14.9 (14.1-15.7)	19.0 (18.4-19.5)	26.3 (25.6-27.1)	29.6 (28.7-30.4)
Follow-up					
Observed %	52.8 (52.0-53.6)	48.2 (47.1-49.3)	48.8 (48.1-49.4)	39.6 (38.8-40.4)	52.4 (51.5-53.3)
Died %	20.8 (20.2-21.5)	10.9 (10.2-11.6)	7.4 (7.0-7.7)	9.8 (9.3-10.3)	15.0 (14.4-15.7)

Values are mean (SD) for age and % (95% CI) for all other variables.

Table 2 presents the prevalence of each outcome at follow-up by region and sex. ADL disability onset was highest in the US (14.6% for females, 12.1% for males) compared with European regions (7.5-11.6% for females, 9.5-11.5% for males). IADL disability showed a similar pattern, with the US exhibiting the highest rates (13.8% for females, 10.6% for males). Verbal memory decline (defined as a 3-point drop in total word recall) was more evenly distributed across regions, ranging from 24.6% (Eastern European females) to 27.4% (Mediterranean females).

Table 2. Outcome prevalence at follow-up by region and sex

	n (ADL/IADL)	n (VM)	ADL onset %	IADL onset %	VM decline %
United States					
Female	4,673	4,606	14.6 (13.6-15.6)	13.8 (12.8-14.8)	25.6 (24.3-26.9)
Male	3,184	3,030	12.1 (10.9-13.2)	10.6 (9.5-11.7)	26.7 (25.2-28.3)
Nordic					
Female	2,019	2,060	7.5 (6.4-8.7)	5.2 (4.2-6.1)	25.8 (23.9-27.7)
Male	1,698	1,755	9.7 (8.3-11.1)	4.0 (3.1-5.0)	25.9 (23.9-28.0)
Western					
Female	5,766	4,937	9.7 (8.9-10.5)	5.0 (4.5-5.6)	27.0 (25.7-28.2)
Male	4,503	4,000	9.5 (8.6-10.3)	4.1 (3.5-4.6)	27.0 (25.6-28.3)
Mediterranean					
Female	2,985	2,786	11.6 (10.4-12.7)	7.2 (6.3-8.1)	27.4 (25.7-29.0)
Male	2,292	2,153	9.8 (8.6-11.1)	5.6 (4.7-6.6)	26.8 (24.9-28.6)
Eastern					
Female	3,882	3,486	11.2 (10.2-12.2)	8.0 (7.2-8.9)	24.6 (23.1-26.0)
Male	2,281	2,041	11.5 (10.2-12.8)	7.4 (6.3-8.5)	26.0 (24.1-27.9)

Values are % (95% CI). ADL = activities of daily living; IADL = instrumental activities of daily living; VM = verbal memory.

Education and disability onset: logistic regression results

Table 3 presents the odds ratios for low vs. high educational attainment across the three nested models, stratified by region, sex, and outcome. All estimates are from IPW-weighted models. Full model coefficients for all three disability categories and both sexes can be found in the Supplementary Material, Tables S1-S6.

In Model 1 (adjusted for age only), low education was associated with significantly elevated odds of ADL onset for both females and males in the US, Nordic Europe, Western Europe, and Eastern Europe. Adjustment for sociodemographic factors (Model 2) and health conditions (Model 3) progressively attenuated these associations. Significant effects persisted in the full model for females and males in the US and Nordic Europe, and females in Eastern Europe.

In fully adjusted models, low educational attainment was associated with significantly elevated odds of ADL disability onset among females in the US (OR 1.30, 95% CI 1.07-1.58), Nordic Europe (OR 1.75, 1.24-2.51), and Eastern Europe (OR 1.49, 1.11-2.03), and among males in the US (OR 1.38, 1.10-1.74) and Nordic Europe (OR 1.43, 1.04-1.95); no significant associations were found in Western or Mediterranean Europe for either sex. Educational gradients in IADL disability were stronger and more geographically widespread, with the largest associations observed in Eastern European females (OR 3.10, 2.09-4.74) and US males (OR 2.29, 1.79-2.93). Mediterranean Europe was the only region showing no significant education gradient for either physical disability outcome. In contrast, low educational attainment showed no consistent association with verbal memory decline in any region or sex, with point estimates clustering near the null regardless of adjustment level. The only marginal associations were observed among females in Eastern and Western Europe, but these were in opposite directions and after FDR correction were deemed as not robust enough. This null pattern was consistent across all three model specifications.

The different sensitivity analyses supported the robustness of the main findings (Tables S7-S11, Figures S1-S3 in the Supplementary Material). Nagelkerke pseudo-R^2 values can be found in the Supplementary Material, Table S12.

Table 3. Odds ratios for low vs. high educational attainment across nested models

ADL disability onset						
	Females			**Males**		
	Model 1	**Model 2**	**Model 3**	**Model 1**	**Model 2**	**Model 3**
United States	2.02 (1.68–2.42)***	1.33 (1.09–1.62)**	1.30 (1.07–1.58)**	1.96 (1.59–2.43)***	1.46 (1.16–1.83)**	1.38 (1.10–1.74)**
Nordic	2.08 (1.55–2.81)***	1.90 (1.34–2.71)***	1.75 (1.24–2.51)**	1.55 (1.17–2.05)**	1.48 (1.08–2.02)*	1.43 (1.04–1.95)*
Western	1.47 (1.24–1.75)***	1.24 (1.01–1.52)*	1.18 (0.96–1.45)	1.60 (1.34–1.91)***	1.09 (0.90–1.34)	1.08 (0.88–1.32)
Mediterranean	1.57 (1.18–2.12)**	1.41 (0.99–2.04)	1.26 (0.88–1.83)	1.33 (0.99–1.80)	1.03 (0.75–1.43)	0.98 (0.71–1.37)
Eastern	2.05 (1.62–2.62)***	1.60 (1.19–2.17)**	1.49 (1.11–2.03)**	1.84 (1.43–2.39)***	1.32 (1.00–1.76)	1.28 (0.96–1.71)
IADL disability onset						
	Females			**Males**		
	Model 1	**Model 2**	**Model 3**	**Model 1**	**Model 2**	**Model 3**
United States	1.80 (1.49–2.19)***	1.30 (1.06–1.59)*	1.29 (1.05–1.58)*	3.17 (2.52–4.01)***	2.49 (1.95–3.17)***	2.29 (1.79–2.93)***
Nordic	1.64 (1.14–2.37)**	1.67 (1.12–2.51)*	1.59 (1.07–2.41)*	1.24 (0.82–1.87)	1.29 (0.83–2.02)	1.29 (0.83–2.01)
Western	1.86 (1.47–2.37)***	1.59 (1.20–2.13)**	1.56 (1.18–2.10)**	2.58 (1.99–3.36)***	2.06 (1.55–2.74)***	2.07 (1.56–2.76)***
Mediterranean	1.90 (1.31–2.83)**	1.24 (0.81–1.98)	1.12 (0.72–1.80)	1.63 (1.09–2.55)*	1.34 (0.87–2.15)	1.34 (0.87–2.16)
Eastern	2.73 (2.05–3.68)***	3.23 (2.19–4.92)***	3.10 (2.09–4.74)***	2.46 (1.79–3.43)***	2.05 (1.45–2.95)***	2.03 (1.43–2.92)***
Verbal memory decline						
	Females			**Males**		
	Model 1	**Model 2**	**Model 3**	**Model 1**	**Model 2**	**Model 3**
United States	0.98 (0.84–1.16)	0.90 (0.76–1.07)	0.91 (0.77–1.07)	1.04 (0.87–1.23)	0.98 (0.82–1.17)	0.94 (0.79–1.13)
Nordic	1.02 (0.84–1.23)	1.15 (0.93–1.42)	1.12 (0.91–1.38)	0.97 (0.79–1.20)	1.07 (0.86–1.33)	1.08 (0.86–1.34)
Western	1.07 (0.95–1.20)	1.14 (1.00–1.30)	1.15 (1.01–1.31)*	1.04 (0.92–1.19)	1.00 (0.87–1.15)	0.99 (0.86–1.14)
Mediterranean	0.91 (0.77–1.08)	0.83 (0.69–1.01)	0.86 (0.71–1.05)	0.99 (0.84–1.18)	1.00 (0.84–1.20)	0.99 (0.83–1.19)
Eastern	0.84 (0.71–0.99)*	0.80 (0.65–0.97)*	0.79 (0.64–0.96)*	0.95 (0.79–1.15)	0.93 (0.76–1.13)	0.92 (0.76–1.13)
Note: Values are odds ratios (95% CI). Model 1 = age-adjusted; Model 2 = additionally adjusted for self-rated health, partnership status, and mobility limitations; Model 3 = fully adjusted. * $p < 0.05$ ** $p < 0.01$ *** $p < 0.001$						

Attenuation of education effects

Table 4 presents results of the attenuation analysis. For ADL disability, sociodemographic and health covariates explained a substantial share of the education gradient. In the US, total attenuation was 65.9% for females and 58.0% for males, indicating that more than half of the crude education effect operated through the measured mediators. Western European males showed the highest attenuation (84.8%), suggesting that health conditions largely account for the education-ADL association in that context. Nordic females showed comparatively modest attenuation (31.1%), indicating that the education-ADL gradient in Nordic countries operates through unmeasured pathways among females.

For IADL disability, attenuation was generally lower (22-62%), consistent with IADL limitations being influenced by cognitive and social factors not fully captured by health conditions. Notably, in Eastern European females, the IADL-education effect showed virtually no attenuation (0.3%), with the OR remaining at approximately 3.0 from the parsimonious to the full model. This is surprising and suggests that the mechanisms linking education to IADL in Eastern European contexts operate almost entirely outside standard chronic disease pathways.

Figure S4 in the Supplementary Material displays forest plots of the odds ratios for low (vs. high) education across the three nested models for females and males, illustrating the progressive attenuation from Model 1 to Model 3.

Table 4. Attenuation of education effects on disability (ADL and IADL)

Panel A: ADL disability onset						
	Females			**Males**		
Region	**OR Model 1**	**OR Model 3**	**Attenuation**	**OR Model 1**	**OR Model 3**	**Attenuation**
United States	2.02 (1.68–2.42)***	1.30 (1.07–1.58)**	**65.9%**	1.96 (1.59–2.43)***	1.38 (1.10–1.74)**	**58.0%**
Nordic	2.08 (1.55–2.81)***	1.75 (1.24–2.51)**	**31.1%**	1.55 (1.17–2.05)**	1.43 (1.04–1.95)*	**12.8%**
Western	1.47 (1.24–1.75)***	1.18 (0.96–1.45)	**49.3%**	1.60 (1.34–1.91)***	1.08 (0.88–1.32)	**84.8%**
Mediterranean	1.57 (1.18–2.12)**	1.26 (0.88–1.83)	**36.3%**	1.33 (0.99–1.80)	0.98 (0.71–1.37)	**107.9%**
Eastern	2.05 (1.62–2.62)***	1.49 (1.11–2.03)**	**54.2%**	1.84 (1.43–2.39)***	1.28 (0.96–1.71)	**71.6%**
Panel B: IADL disability onset						
	Females			**Males**		
Region	**OR Model 1**	**OR Model 3**	**Attenuation**	**OR Model 1**	**OR Model 3**	**Attenuation**
United States	1.80 (1.49–2.19)***	1.29 (1.05–1.58)*	**61.7%**	3.17 (2.52–4.01)***	2.29 (1.79–2.93)***	**36.2%**
Nordic	1.64 (1.14–2.37)**	1.59 (1.07–2.41)*	**25.4%**	1.24 (0.82–1.87)	1.29 (0.83–2.01)	**−18.7%**
Western	1.86 (1.47–2.37)***	1.56 (1.18–2.10)**	**27.6%**	2.58 (1.99–3.36)***	2.07 (1.56–2.76)***	**22.4%**
Mediterranean	1.90 (1.31–2.83)**	1.12 (0.72–1.80)	**71.8%**	1.63 (1.09–2.55)*	1.34 (0.87–2.16)	**50.0%**
Eastern	2.73 (2.05–3.68)***	3.10 (2.09–4.74)***	**0.3%**	2.46 (1.79–3.43)***	2.03 (1.43–2.92)***	**24.0%**

Note: Values are odds ratios (95% CI) for low vs. high education. Model 1 = age-adjusted; Model 3 = fully adjusted. Negative attenuation indicates modest increase after adjustment. * $p < 0.05$ ** $p < 0.01$ *** $p < 0.001$

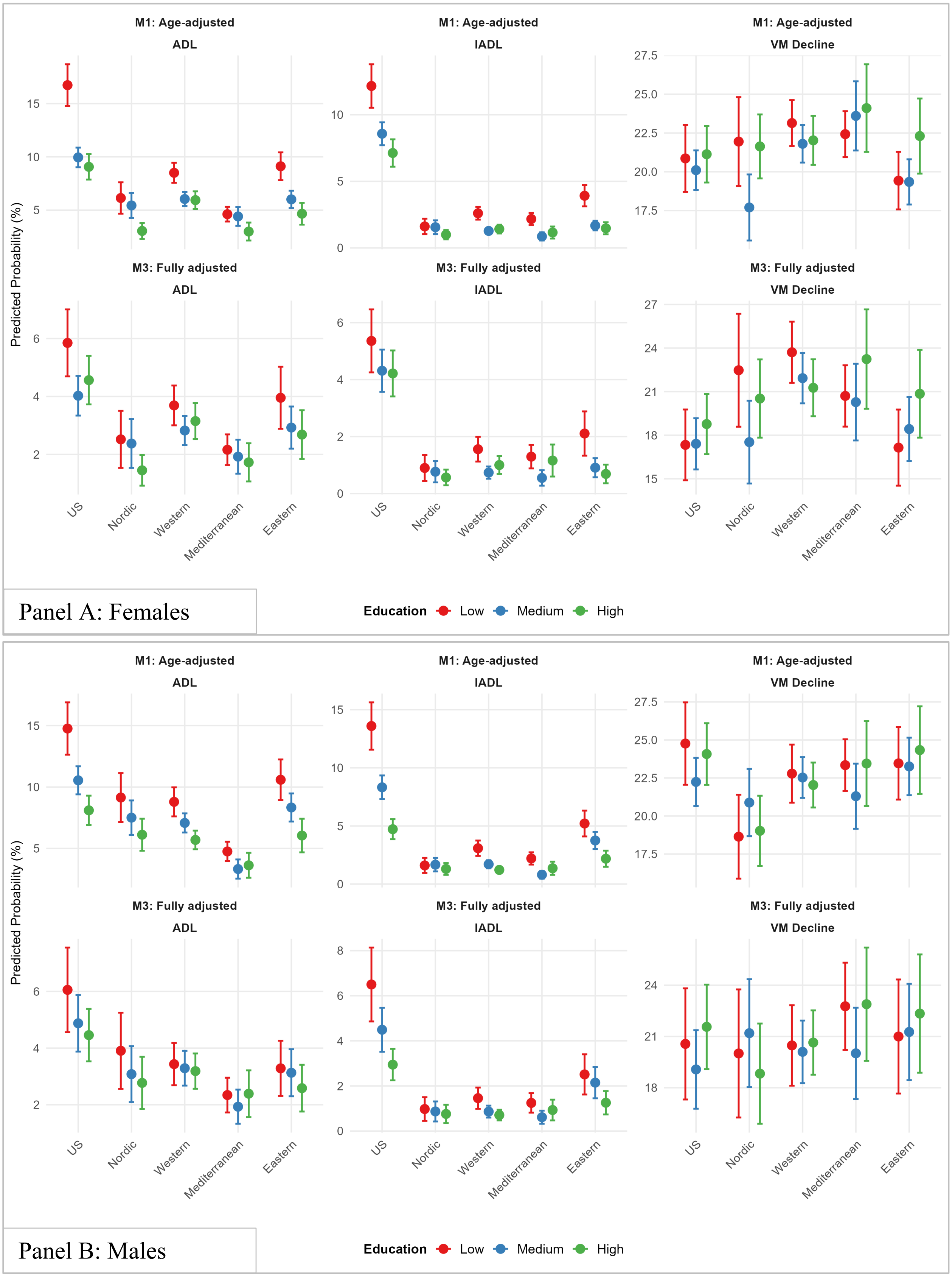
Predicted probabilities

Figure 1 illustrates the predicted probabilities of each outcome by education level, computed from the full model under a healthy counterfactual profile. Absolute risk differences between education groups were modest for ADL disability (typically 1-3 percentage points), somewhat larger for IADL disability, especially in the US (6.5% for low-educated males vs. 2.9% for high-educated males), and in Eastern Europe (2.1% for low-educated females vs. 0.7% for high-educated females), and negligible for verbal memory decline. Under the average covariate profile (where individuals carry the sample-average comorbidity burden), predicted probabilities were uniformly higher, but the education gradient patterns remained consistent. Full results are presented in the Supplementary Material, Tables S13 and S14.

Figure 1, panels A and B illustrate the predicted probabilities across education levels for females and males, respectively. The education gradient is visually apparent for ADL and IADL outcomes, particularly in the US and Eastern Europe, while predicted probabilities for verbal memory decline are nearly flat across education levels in all regions. Figure S5 in the Supplementary Material presents predicted probabilities under the average covariate profile, where covariates are set to observed sample means. Under this specification, predicted disability rates were higher because the average individual carries some comorbidity burden, but the relative education gradient was preserved.

Figure 1 also highlights notable differences in predicted probabilities between the US and European regions. Focusing on the fully adjusted models, a clear gap emerges between the US and most European regions in IADL disability probabilities for both women and men, with the exception of Eastern Europe. Among women, the predicted ADL disability probability for highly educated Americans exceeds that of low-educated women in the Nordic and Mediterranean countries. Among men, only the latter comparison holds. No analogous regional distinctions are observed for verbal memory decline.

Figure 1. Predicted probabilities of ADL, IADL, and verbal memory by education, 95% CI



Discussion

This cross-national study examines educational inequalities in the onset of ADL disability, IADL disability, and verbal memory decline among adults aged 50 and older across the United States and four European regions over the course of a decade. Three findings stand out. Firstly, the education gradient in functional disability onset was strongest and most persistent in the US and Eastern Europe. Secondly, IADL gradients were generally stronger and less attenuated by health conditions than ADL gradients, suggesting that pre-existing health conditions do not play a large role in changes in instrumental functioning. Thirdly, education showed no consistent association with verbal memory decline in any region or sex.

Within-region findings

Our results are largely consistent with research that finds an association between socioeconomic indicators and disability. For example, Stolz et al. (2025) find higher educational attainment to be associated with a prolonged independent living among those aged 65 and older in Austria, and Arpino & Solé-Auró (2019) find an educational gradient across health measures among Europeans aged 50 and older. This is in line with research that finds an association between higher socioeconomic status and lower mortality in high income countries (Huisman et al., 2004), including in Nordic welfare states, such as Denmark (Brønnum-Hansen et al., 2021; Strozza et al., 2025).

The null findings for verbal memory decline across all regions and both sexes merit careful interpretation. The cognitive reserve hypothesis suggests that higher-educated individuals build greater neural redundancy across the life course, but may eventually decline at similar rates once reserve is depleted, such that education predicts the level of cognitive function rather than the rate of decline over a given follow-up window (Stern, 2002, 2012). This interpretation is supported by recent large-scale evidence; Fjell et al. (2025), analyzing over 407,000 episodic memory assessments across 33 Western countries, found that education was associated with better memory but did not protect against age-related decline, concluding that the association reflects early-life factors rather than neuroprotective effects. Bayesian analyses of longitudinal cohort data have similarly supported the null hypothesis that education does not alter the rate of episodic memory decline (Lövdén et al., 2020).

Our threshold-based measure of verbal memory decline (a 3-point drop in total word recall or close to 1SD) may be better suited to capturing abrupt transitions than the gradual gradient differences that education likely produces. The mortality analyses provide a complementary explanation: low-educated individuals in the US and Eastern Europe faced substantially higher mortality during follow-up, meaning the most cognitively vulnerable among them were selectively removed from the analytical sample. The FDR correction results confirm this interpretation; all ADL and IADL associations held after correction, while verbal memory associations did not.

Cross-country comparative findings

Findings of our cross-country comparison extend a growing body of evidence on socioeconomic inequalities in late-life health across the United States and Europe. Prior work using HRS, ELSA, and SHARE has consistently shown that disability levels are highest in the United States and lowest in Northern and Western Europe, with weaker social policies and greater inequality associated with higher burden and earlier onset (Wahrendorf et al., 2013). Recent work by Machado et al. (2025) demonstrated that wealth is strongly associated with mortality across both settings, with the gradient substantially wider in the United States than in Europe, and with the wealthiest Americans faring no better than the poorest Northern and Western Europeans in terms of survival. Our results suggest that this trend also applies to functional disability, and particularly to IADL disability. From our study, the highest educated females from the United States had a higher predicted probability of developing IADL disabilities than the least educated women in all four European regions. The same was seen among the highest educated US males, apart from Eastern European males. This geographic patterning is consistent with the hypothesis that steeper socioeconomic stratification in the United States, reflected in greater inequality in access to healthcare, occupational exposures, and material resources across the life course translates into larger health disparities in older age (Avendano & Kawachi, 2014; Bergeron-Boucher et al., 2024; Cutler & Lleras-Muney, 2010; Zaninotto et al., 2020).

An intriguing finding is the absence of a clear “Nordic advantage” in buffering educational inequalities. Nordic women showed significant education-ADL gradients, consistent with the “Nordic paradox” in health inequalities research (Mackenbach, 2012). This may reflect that in Nordic contexts, the low-education group represents a particularly selected and vulnerable subpopulation. Because educational expansion has pushed the majority into higher attainment, those who remain with low education are increasingly concentrated among individuals with compounding disadvantages, making the residual gradient difficult to eliminate regardless of welfare state policies (Brønnum-Hansen & Baadsgaard, 2012; Enroth et al., 2022; Strozza et al., 2025). The ADL gradient among Nordic females appears to be driven not by educational disadvantage, but by unmeasured health or social conditions that cluster disproportionately within the low-education group, suggesting that education serves as a marker rather than a mechanism of inequality in this context.

The attenuation of education effects following adjustment for pre-existing health conditions indicates that a meaningful share of the education-disability gradient operates through disease pathways. In the US, over 60% of the crude education-ADL association was explained by the measured mediators for females, consistent with evidence that education shapes health behaviors, occupational exposures, and healthcare access in ways that ultimately determine chronic disease burden (Avendano & Kawachi, 2014; Zajacova & Lawrence, 2018).Cross-national analyses have similarly identified low income, excess body weight, and smoking as key mediators of educational inequalities in disability-free life expectancy, particularly in Eastern Europe (Rubio Valverde, Mackenbach, Bopp, et al., 2021).

The notably low attenuation of IADL gradients compared with ADL gradients deserves specific attention. IADL tasks (managing finances, medications, shopping, and meal preparation) draw heavily on cognitive and organizational capacities that track educational attainment independently of physical health status. This is consistent with Verbrugge and Jette's disablement model, which distinguishes between limitations in basic physical functioning and the broader capacity for independent living in social context (Verbrugge & Jette, 1994).

The regional patterning of our results raises important questions about the role of welfare state structures in moderating educational inequalities in disability. The relatively modest ADL gradients observed in Western Europe, and the complete absence of significant physical disability gradients in Mediterranean Europe, may reflect the buffering effects of more comprehensive social protection systems, including healthcare access, sickness and disability benefits, and stronger labor market protections for less-skilled workers (Mackenbach et al., 2008). In contrast, the persistence of large gradients in the US, where disability onset is closely tied to insurance coverage, out-of-pocket healthcare costs, and occupational injury risk, is consistent with evidence that the relationship between socioeconomic position and health is more pronounced in more unequal societies (Bergeron-Boucher et al., 2024; Chetty et al., 2016). The Eastern European pattern is distinct; large IADL gradients that are essentially unattenuated by pre-existing health adjustment, alongside moderate ADL gradients, consistent with evidence that educational disparities in disability-free life expectancy are largest in Central and Eastern Europe, and impose a disproportionate burden on women in that region (Stonkute et al., 2023). This may reflect both the legacy of diverse communist occupational structures, as well as the rapid health system transformations of the post-1990 period, which may have widened inequalities in access to preventive and rehabilitative care.

Limitations

Several limitations of this study warrant consideration. Firstly, although we adjusted for a broad set of health conditions and sociodemographic factors, residual confounding by unmeasured variables remains possible. The study design considering healthy individuals at the baseline, while appropriate for studying long-term disability incidence, introduces differential selection across regions, since the proportion excluded due to baseline limitations varies with the region-specific prevalence of prior disability. Additionally, our verbal memory measure, while harmonized across HRS and SHARE, relies on a single threshold and may not capture the full spectrum of cognitively meaningful decline. Finally, regional groupings necessarily obscure within-region heterogeneity: Estonia and Slovenia, for instance, share an Eastern European classification but differ substantially in educational systems and exposures to communist regimes. Furthermore, our models estimate average effects across the age range of the analytic sample, and it is possible that the relationship between education and disability onset is age-specific, with gradients that strengthen, attenuate, or reverse at different points in later life.

Conclusions

These findings have implications for efforts to reduce late-life disability burden. The large educational gradients in IADL disability, particularly in the US and Eastern Europe, suggest that targeting less-educated older adults for early functional assessment and IADL support could meaningfully reduce disparities in independent living. The partial mediation by pre-existing health conditions further implies that disease prevention and management across the adult life course remains a critical lever. At the same time, the persistence of significant education effects even after full adjustment, particularly in the US and Nordic Europe, points to broader social and structural determinants that disease management alone cannot address, echoing the conclusion of Machado et al. (2025) that comparative health disadvantage in the United States reflects systemic factors operating across the full socioeconomic distribution.

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Supplementary material

Table S1. Full model coefficients for ADL disability onset by region (IPW-weighted) – females

Predictor	United States	Nordic	Western	Mediterranean	Eastern
Intercept	0.00 (0.00-0.00)***	0.00 (0.00-0.00)***	0.00 (0.00-0.00)***	0.00 (0.00-0.00)***	0.00 (0.00-0.00)***
Edu: Medium (vs High)	0.88 (0.75-1.03)	1.65 (1.18-2.34)**	0.89 (0.73-1.10)	1.12 (0.74-1.70)	1.09 (0.82-1.48)
Edu: Low (vs High)	1.30 (1.07-1.58)**	1.75 (1.24-2.51)**	1.18 (0.96-1.45)	1.26 (0.88-1.83)	1.49 (1.11-2.03)**
Age (per year)	1.07 (1.06-1.08)***	1.08 (1.06-1.09)***	1.06 (1.05-1.07)***	1.12 (1.10-1.13)***	1.07 (1.06-1.09)***
Poor self-rated health	1.93 (1.66-2.23)***	1.92 (1.43-2.57)***	2.50 (2.13-2.94)***	2.00 (1.62-2.47)***	1.35 (1.10-1.68)**
Has partner	0.82 (0.73-0.94)**	0.93 (0.68-1.30)	0.72 (0.60-0.87)***	0.59 (0.42-0.84)**	0.79 (0.62-1.01)
Hypertension	1.13 (0.98-1.29)	1.24 (0.93-1.64)	1.23 (1.05-1.44)*	1.38 (1.12-1.69)**	1.17 (0.94-1.47)
Diabetes	1.09 (0.94-1.27)	0.86 (0.56-1.29)	1.38 (1.10-1.71)**	1.43 (1.11-1.83)**	1.33 (1.04-1.69)*
Obese (BMI ≥30)	1.22 (1.07-1.40)**	1.62 (1.16-2.25)**	1.49 (1.25-1.77)***	1.35 (1.08-1.68)**	1.41 (1.14-1.74)**
Mobility limitation	2.45 (2.14-2.80)***	2.90 (2.16-3.90)***	1.84 (1.56-2.18)***	1.88 (1.52-2.32)***	2.15 (1.75-2.65)***
Ever smoker	1.17 (1.03-1.32)*	1.44 (1.10-1.90)**	1.15 (0.99-1.34)	1.03 (0.82-1.29)	1.06 (0.85-1.31)

Table S2. Full model coefficients for ADL disability onset by region (IPW-weighted) – males

Predictor	United States	Nordic	Western	Mediterranean	Eastern
Intercept	0.00 (0.00-0.01)***	0.00 (0.00-0.00)***	0.00 (0.00-0.00)***	0.00 (0.00-0.00)***	0.00 (0.00-0.00)***
Education: Medium (vs High)	1.10 (0.91-1.32)	1.11 (0.83-1.51)	1.03 (0.87-1.23)	0.80 (0.55-1.18)	1.22 (0.93-1.60)
Education: Low (vs High)	1.38 (1.10-1.74)**	1.43 (1.04-1.95)*	1.08 (0.88-1.32)	0.98 (0.71-1.37)	1.28 (0.96-1.71)
Age (per year)	1.04 (1.03-1.05)***	1.05 (1.04-1.07)***	1.08 (1.07-1.09)***	1.12 (1.11-1.14)***	1.08 (1.06-1.09)***
Poor self-rated health	1.27 (1.05-1.53)*	2.60 (1.96-3.42)***	2.43 (2.06-2.86)***	1.82 (1.49-2.23)***	2.48 (2.02-3.04)***
Has partner	0.73 (0.61-0.88)**	1.21 (0.79-1.94)	0.62 (0.49-0.79)***	0.61 (0.39-1.00)*	0.79 (0.55-1.15)
Hypertension	1.29 (1.09-1.52)**	1.38 (1.08-1.78)*	1.27 (1.09-1.48)**	0.98 (0.81-1.19)	1.28 (1.05-1.57)*
Diabetes	0.98 (0.82-1.17)	1.02 (0.70-1.45)	1.26 (1.04-1.52)*	1.82 (1.45-2.27)***	1.13 (0.89-1.43)
Obese (BMI ≥30)	1.34 (1.14-1.57)***	1.35 (0.97-1.85)	1.49 (1.24-1.78)***	1.60 (1.28-1.99)***	1.27 (1.02-1.57)*
Mobility limitation	2.46 (2.10-2.89)***	2.23 (1.60-3.07)***	2.35 (1.97-2.81)***	1.79 (1.44-2.21)***	1.82 (1.48-2.23)***
Ever smoker	1.25 (1.06-1.49)**	1.81 (1.39-2.38)***	1.00 (0.86-1.17)	1.01 (0.83-1.22)	1.24 (1.01-1.51)*

Table S3. Full model coefficients for IADL disability onset by region (IPW-weighted) – females

Predictor	US	Nordic	Western	Mediterranean	Eastern
Intercept	0.00 (0.00-0.00)***	0.00 (0.00-0.00)***	0.00 (0.00-0.00)***	0.00 (0.00-0.00)***	0.00 (0.00-0.00)***
Education: Medium (vs High)	1.02 (0.87-1.21)	1.36 (0.90-2.08)	0.73 (0.54-1.00)	0.47 (0.26-0.86)*	1.32 (0.88-2.03)
Education: Low (vs High)	1.29 (1.05-1.58)*	1.59 (1.07-2.41)*	1.56 (1.18-2.10)**	1.12 (0.72-1.80)	3.10 (2.09-4.74)***
Age (per year)	1.09 (1.08-1.09)***	1.18 (1.16-1.21)***	1.14 (1.13-1.16)***	1.18 (1.16-1.20)***	1.17 (1.15-1.20)***
Poor self-rated health	1.66 (1.43-1.94)***	1.98 (1.40-2.78)***	2.00 (1.59-2.50)***	1.85 (1.43-2.40)***	1.63 (1.25-2.13)***
Has partner	0.89 (0.79-1.02)	1.69 (1.11-2.63)*	1.14 (0.85-1.55)	3.87 (1.99-8.39)***	1.53 (1.08-2.21)*
Hypertension	1.37 (1.20-1.58)***	1.12 (0.81-1.55)	1.02 (0.82-1.27)	1.14 (0.88-1.46)	1.11 (0.84-1.47)
Diabetes	1.00 (0.85-1.17)	0.91 (0.55-1.45)	0.98 (0.70-1.35)	1.31 (0.96-1.77)	1.76 (1.31-2.33)***
Obese (BMI ≥30)	0.83 (0.72-0.96)*	1.52 (1.00-2.28)*	1.21 (0.93-1.56)	1.06 (0.79-1.40)	1.07 (0.82-1.40)
Mobility limitation	2.27 (1.98-2.60)***	2.07 (1.46-2.93)***	1.79 (1.42-2.26)***	1.27 (0.98-1.65)	1.34 (1.04-1.72)*
Ever smoker	1.10 (0.97-1.25)	1.32 (0.96-1.82)	1.22 (0.98-1.52)	0.82 (0.59-1.11)	0.87 (0.65-1.17)

Table S4. Full model coefficients for IADL disability onset by region (IPW-weighted) – males

Predictor	US	Nordic	Western	Mediterranean	Eastern
Intercept	0.00 (0.00-0.00)***	0.00 (0.00-0.00)***	0.00 (0.00-0.00)***	0.00 (0.00-0.00)***	0.00 (0.00-0.00)***
Education: Medium (vs High)	1.55 (1.26-1.91)***	1.15 (0.75-1.78)	1.22 (0.93-1.61)	0.66 (0.37-1.18)	1.73 (1.23-2.47)**
Education: Low (vs High)	2.29 (1.79-2.93)***	1.29 (0.83-2.01)	2.07 (1.56-2.76)***	1.34 (0.87-2.16)	2.03 (1.43-2.92)***
Age (per year)	1.07 (1.06-1.08)***	1.12 (1.10-1.15)***	1.13 (1.11-1.14)***	1.14 (1.12-1.16)***	1.11 (1.09-1.13)***
Poor self-rated health	1.39 (1.14-1.69)**	2.58 (1.75-3.77)***	1.80 (1.42-2.29)***	1.93 (1.50-2.48)***	2.17 (1.70-2.77)***
Has partner	0.91 (0.74-1.11)	1.03 (0.56-2.08)	0.89 (0.61-1.35)	2.70 (1.05-9.93)	1.31 (0.79-2.32)
Hypertension	1.22 (1.03-1.45)*	1.47 (1.03-2.10)*	1.34 (1.07-1.68)**	1.05 (0.83-1.34)	1.24 (0.97-1.57)
Diabetes	1.03 (0.86-1.24)	1.06 (0.63-1.70)	1.20 (0.91-1.57)	1.32 (0.99-1.75)	1.26 (0.94-1.66)
Obese (BMI ≥30)	1.13 (0.95-1.34)	1.21 (0.73-1.94)	1.11 (0.84-1.46)	1.20 (0.90-1.58)	0.70 (0.52-0.94)*

Predictor	US	Nordic	Western	Mediterranean	Eastern
Mobility limitation	1.77 (1.49-2.09)***	1.55 (0.98-2.39)	2.09 (1.62-2.68)***	1.31 (1.00-1.71)*	1.40 (1.09-1.79)**
Ever smoker	1.38 (1.16-1.66)***	1.37 (0.95-1.99)	1.14 (0.92-1.43)	1.21 (0.95-1.54)	1.21 (0.95-1.53)

Table S5. Full model coefficients for verbal memory disability onset by region (IPW-weighted) – females

Predictor	**US**	**Nordic**	**Western**	**Mediterranean**	**Eastern**
Intercept	0.01 (0.01-0.02)***	0.04 (0.02-0.08)***	0.04 (0.03-0.06)***	0.06 (0.03-0.10)***	0.04 (0.02-0.07)***
Education: Medium (vs High)	0.91 (0.81-1.03)	0.82 (0.68-1.00)*	1.04 (0.92-1.18)	0.84 (0.67-1.05)	0.86 (0.72-1.03)
Education: Low (vs High)	0.91 (0.77-1.07)	1.12 (0.91-1.38)	1.15 (1.01-1.31)*	0.86 (0.71-1.05)	0.79 (0.64-0.96)*
Age (per year)	1.05 (1.04-1.06)***	1.03 (1.02-1.04)***	1.03 (1.03-1.04)***	1.03 (1.02-1.03)***	1.04 (1.03-1.05)***
Poor self-rated health	1.19 (1.04-1.37)*	1.11 (0.89-1.38)	1.09 (0.96-1.22)	1.10 (0.95-1.27)	0.94 (0.82-1.09)
Has partner	0.92 (0.83-1.02)	1.01 (0.81-1.27)	0.88 (0.77-1.01)	1.11 (0.88-1.40)	0.80 (0.67-0.94)**
Hypertension	0.90 (0.80-1.00)*	0.98 (0.82-1.17)	1.10 (0.99-1.22)	1.13 (0.99-1.30)	0.94 (0.81-1.08)
Diabetes	1.08 (0.95-1.24)	1.29 (0.96-1.73)	1.19 (0.99-1.41)	1.15 (0.94-1.41)	0.95 (0.77-1.16)
Obese (BMI ≥30)	1.02 (0.91-1.14)	1.23 (0.97-1.55)	0.87 (0.76-0.99)*	0.76 (0.64-0.91)**	1.18 (1.01-1.38)*
Mobility limitation	1.14 (1.02-1.27)*	0.93 (0.74-1.17)	0.93 (0.81-1.06)	0.97 (0.83-1.13)	1.09 (0.93-1.28)
Ever smoker	1.20 (1.08-1.33)***	1.03 (0.87-1.21)	0.94 (0.85-1.04)	1.25 (1.08-1.44)**	1.16 (1.00-1.34)

Table S6. Full model coefficients for verbal memory disability onset by region (IPW-weighted) – males

Predictor	**US**	**Nordic**	**Western**	**Mediterranean**	**Eastern**
Intercept	0.05 (0.03-0.08)***	0.02 (0.01-0.05)***	0.04 (0.03-0.06)***	0.06 (0.03-0.10)***	0.11 (0.05-0.21)***
Education: Medium (vs High)	0.86 (0.75-0.98)*	1.16 (0.96-1.41)	0.97 (0.86-1.08)	0.84 (0.68-1.04)	0.94 (0.78-1.13)
Education: Low (vs High)	0.94 (0.79-1.13)	1.08 (0.86-1.34)	0.99 (0.86-1.14)	0.99 (0.83-1.19)	0.92 (0.76-1.13)
Age (per year)	1.03 (1.02-1.04)***	1.04 (1.03-1.05)***	1.03 (1.03-1.04)***	1.03 (1.02-1.03)***	1.02 (1.01-1.03)***
Poor self-rated health	1.09 (0.93-1.28)	1.25 (0.99-1.57)	1.14 (1.01-1.30)*	0.74 (0.64-0.87)***	1.19 (1.02-1.38)*
Has partner	0.83 (0.72-0.96)*	0.98 (0.74-1.30)	0.96 (0.81-1.15)	1.02 (0.77-1.36)	0.80 (0.61-1.05)
Hypertension	1.06 (0.94-1.20)	1.10 (0.92-1.31)	1.01 (0.91-1.12)	0.99 (0.86-1.13)	0.90 (0.78-1.05)
Diabetes	1.17 (1.01-1.35)*	0.93 (0.71-1.22)	1.03 (0.89-1.19)	1.18 (0.99-1.41)	1.27 (1.06-1.53)*
Obese (BMI ≥30)	0.82 (0.72-0.93)**	1.00 (0.79-1.27)	1.16 (1.02-1.32)*	1.22 (1.03-1.44)*	1.07 (0.90-1.26)
Mobility limitation	1.10 (0.96-1.25)	1.11 (0.84-1.47)	1.06 (0.91-1.24)	0.95 (0.80-1.14)	0.95 (0.79-1.14)
Ever smoker	1.19 (1.05-1.35)**	0.91 (0.76-1.07)	1.06 (0.96-1.18)	1.16 (1.02-1.32)*	1.02 (0.88-1.18)

Robustness checks

Five sensitivity analyses were conducted to evaluate the robustness of the main findings:

1. Unweighted estimates. All models were re-estimated without IPW to assess whether the weighting scheme materially affects the education coefficients.
2. Shorter follow-up. Models were re-estimated using SHARE Wave 8 (~7-year follow-up) and HRS Wave 15 (~8-year follow-up) as alternative endpoints, to assess whether results depend on follow-up duration.
3. Separate cognitive components. Verbal memory decline was disaggregated into immediate recall decline and delayed recall decline to examine whether education effects differ by memory component.
4. Mortality as competing outcome. Education-mortality associations were estimated using the same model specifications, to quantify selective survival bias. If low education predicts mortality, disability estimates are conservative because the most vulnerable low-educated individuals are removed from the analytic sample by death.

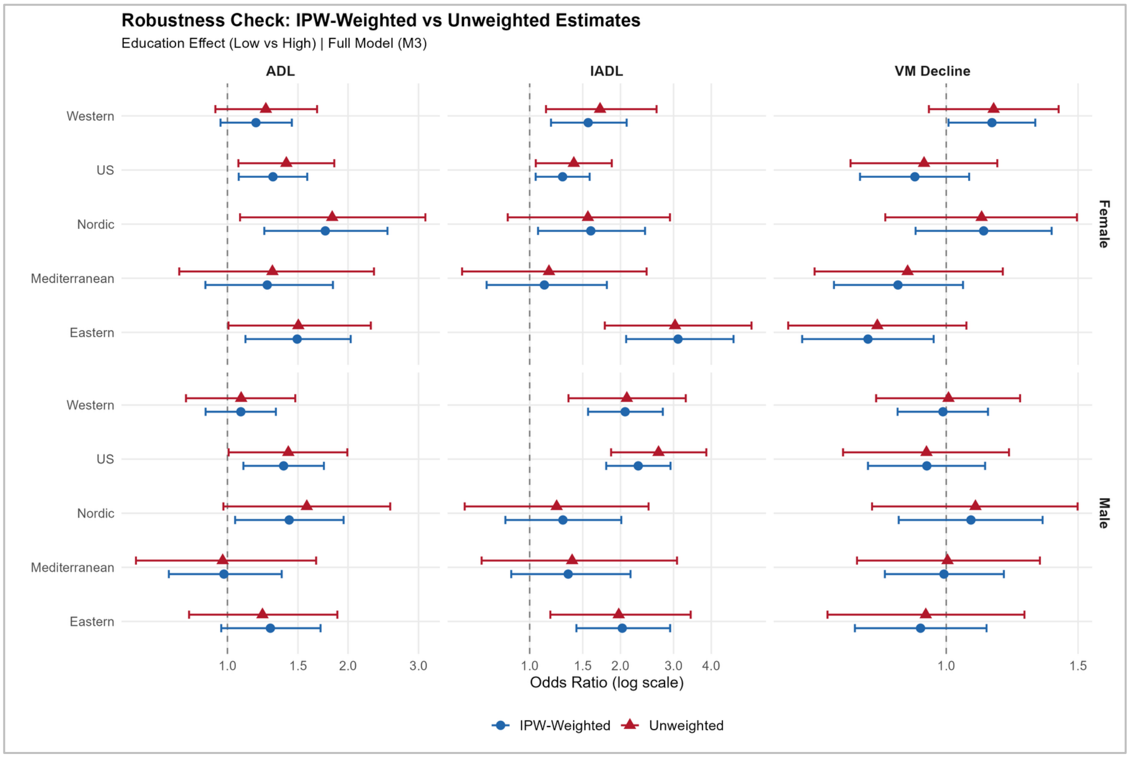
5. False discovery rate (FDR) correction. Benjamini-Hochberg FDR correction and Bonferroni correction were applied to the full set of education coefficient p-values across all region × sex × outcome × model combinations, to address the multiple comparisons problem.

1. IPW-weighted vs. unweighted estimates

Table S7. Full model education Effects: IPW-weighted vs. unweighted

Region	Sex	Outcome	IPW-Weighted	Unweighted
Eastern	Female	ADL	1.49 (1.11-2.03)**	1.50 (1.01-2.28)
Eastern	Male	ADL	1.28 (0.96-1.71)	1.22 (0.80-1.88)
Mediterranean	Female	ADL	1.26 (0.88-1.83)	1.29 (0.76-2.32)
Mediterranean	Male	ADL	0.98 (0.71-1.37)	0.97 (0.59-1.66)
Nordic	Female	ADL	1.75 (1.24-2.51)**	1.83 (1.07-3.12)*
Nordic	Male	ADL	1.43 (1.04-1.95)*	1.58 (0.98-2.55)
US	Female	ADL	1.30 (1.07-1.58)**	1.40 (1.06-1.85)*
US	Male	ADL	1.38 (1.10-1.74)**	1.42 (1.01-1.99)*
Western	Female	ADL	1.18 (0.96-1.45)	1.25 (0.93-1.67)
Western	Male	ADL	1.08 (0.88-1.32)	1.08 (0.79-1.48)
Eastern	Female	IADL	3.10 (2.09-4.74)***	3.03 (1.77-5.44)***
Eastern	Male	IADL	2.03 (1.43-2.92)***	1.97 (1.17-3.42)*
Mediterranean	Female	IADL	1.12 (0.72-1.80)	1.16 (0.60-2.44)
Mediterranean	Male	IADL	1.34 (0.87-2.16)	1.38 (0.69-3.08)
Nordic	Female	IADL	1.59 (1.07-2.41)*	1.56 (0.85-2.92)
Nordic	Male	IADL	1.29 (0.83-2.01)	1.23 (0.61-2.48)
US	Female	IADL	1.29 (1.05-1.58)*	1.40 (1.05-1.87)*
US	Male	IADL	2.29 (1.79-2.93)***	2.67 (1.86-3.85)***
Western	Female	IADL	1.56 (1.18-2.10)**	1.71 (1.13-2.63)*
Western	Male	IADL	2.07 (1.56-2.76)***	2.10 (1.34-3.29)**
Eastern	Female	VM Decline	0.79 (0.64-0.96)*	0.81 (0.61-1.06)
Eastern	Male	VM Decline	0.92 (0.76-1.13)	0.94 (0.69-1.27)
Mediterranean	Female	VM Decline	0.86 (0.71-1.05)	0.89 (0.67-1.19)
Mediterranean	Male	VM Decline	0.99 (0.83-1.19)	1.00 (0.76-1.33)
Nordic	Female	VM Decline	1.12 (0.91-1.38)	1.11 (0.83-1.50)
Nordic	Male	VM Decline	1.08 (0.86-1.34)	1.09 (0.80-1.50)
US	Female	VM Decline	0.91 (0.77-1.07)	0.93 (0.74-1.17)
US	Male	VM Decline	0.94 (0.79-1.13)	0.94 (0.73-1.21)
Western	Female	VM Decline	1.15 (1.01-1.31)*	1.16 (0.95-1.41)
Western	Male	VM Decline	0.99 (0.86-1.14)	1.01 (0.81-1.25)

Figure S1. Comparison of IPW-Weighted vs. Unweighted Estimates



2. Shorter follow-up

Table S8. Education Effects by Follow-Up Duration (Full Model)

Region	Sex	Outcome	~10-Year FU	~8-Year FU
Eastern	Female	ADL	1.49 (1.11-2.03)**	1.89 (1.23-2.98)**
Eastern	Male	ADL	1.28 (0.96-1.71)	1.48 (1.04-2.14)*
Mediterranean	Female	ADL	1.26 (0.88-1.83)	0.96 (0.61-1.56)
Mediterranean	Male	ADL	0.98 (0.71-1.37)	1.23 (0.78-2.03)
Nordic	Female	ADL	1.75 (1.24-2.51)**	1.54 (0.98-2.43)
Nordic	Male	ADL	1.43 (1.04-1.95)*	0.91 (0.59-1.38)
US	Female	ADL	1.30 (1.07-1.58)**	1.14 (0.91-1.43)
US	Male	ADL	1.38 (1.10-1.74)**	1.14 (0.87-1.48)
Western	Female	ADL	1.18 (0.96-1.45)	0.95 (0.73-1.24)
Western	Male	ADL	1.08 (0.88-1.32)	1.01 (0.76-1.34)
Eastern	Female	IADL	3.10 (2.09-4.74)***	5.98 (2.90-14.51)***
Eastern	Male	IADL	2.03 (1.43-2.92)***	3.01 (1.76-5.43)***
Mediterranean	Female	IADL	1.12 (0.72-1.80)	1.21 (0.56-2.98)
Mediterranean	Male	IADL	1.34 (0.87-2.16)	1.38 (0.71-3.02)
Nordic	Female	IADL	1.59 (1.07-2.41)*	0.66 (0.36-1.22)
Nordic	Male	IADL	1.29 (0.83-2.01)	0.76 (0.40-1.43)
US	Female	IADL	1.29 (1.05-1.58)*	1.49 (1.16-1.91)**
US	Male	IADL	2.29 (1.79-2.93)***	2.04 (1.52-2.74)***
Western	Female	IADL	1.56 (1.18-2.10)**	1.39 (0.94-2.09)
Western	Male	IADL	2.07 (1.56-2.76)***	3.56 (2.30-5.63)***

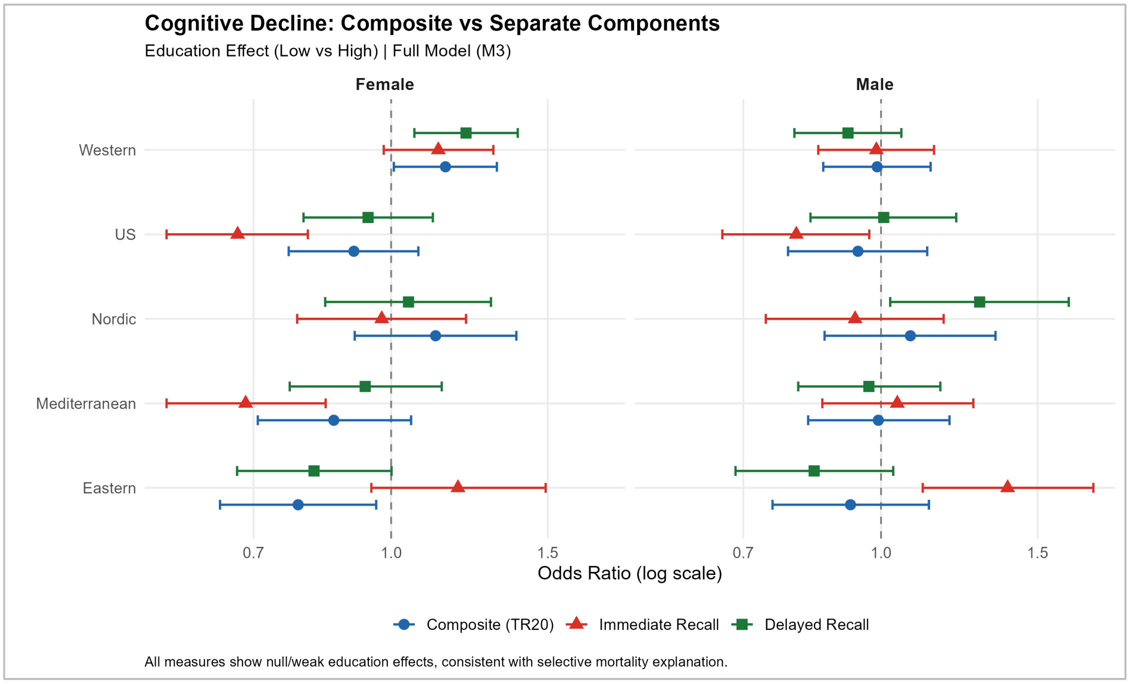
3. Separate cognitive components

Table S9. Education Effects on Immediate and Delayed Recall Decline (Full Model)

Region	Sex	Immediate recall	Delayed recall
Eastern	Female	1.19 (0.95-1.49)	0.82 (0.67-1.00)
Eastern	Male	1.39 (1.11-1.73)**	0.84 (0.69-1.03)

Mediterranean	Female	0.69 (0.56-0.84)***	0.94 (0.77-1.14)
Mediterranean	Male	1.04 (0.86-1.27)	0.97 (0.81-1.17)
Nordic	Female	0.98 (0.78-1.21)	1.05 (0.84-1.29)
Nordic	Male	0.94 (0.74-1.18)	1.29 (1.02-1.63)*
US	Female	0.67 (0.56-0.81)***	0.94 (0.80-1.11)
US	Male	0.80 (0.66-0.97)*	1.01 (0.83-1.22)
Western	Female	1.13 (0.98-1.30)	1.21 (1.06-1.39)**
Western	Male	0.99 (0.85-1.15)	0.92 (0.80-1.05)

Figure S2. Cognitive Component Decomposition

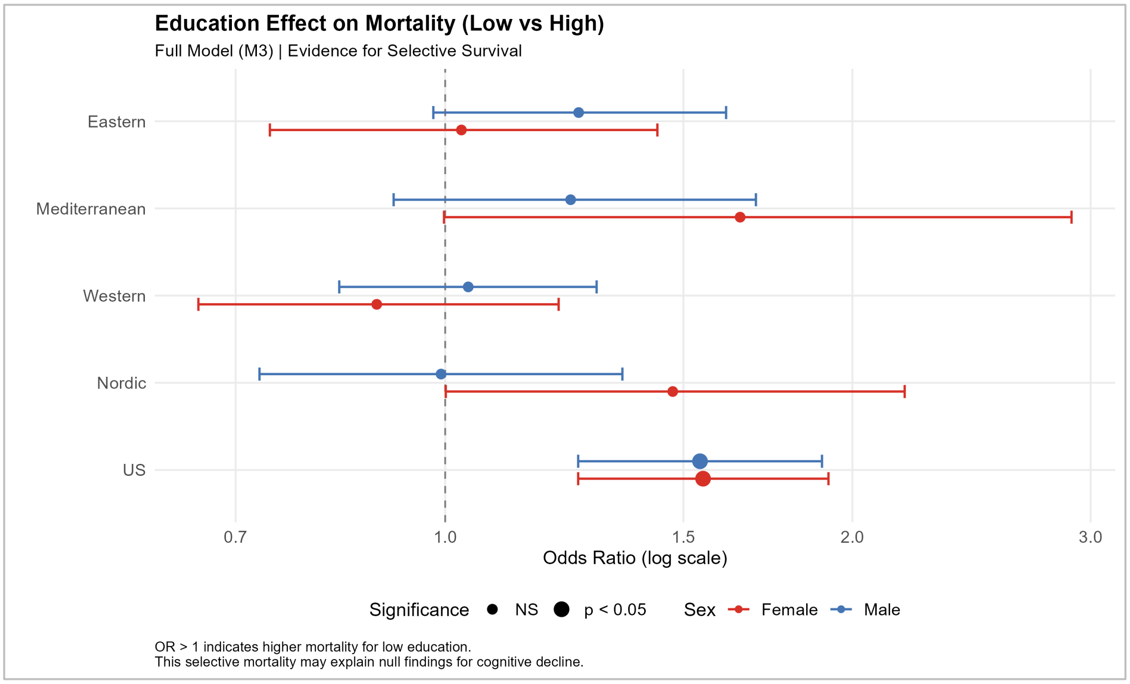


4. Mortality as competing outcome

Table S10. Education and mortality: evidence for selective survival

Region	Sex	Deaths	Model 1 OR (95% CI)	Full Model OR (95% CI)
Eastern	Female	769	1.35 (1.06-1.73)*	1.03 (0.74-1.44)
Eastern	Male	995	1.73 (1.39-2.16)***	1.25 (0.98-1.61)
Mediterranean	Female	515	1.79 (1.21-2.75)**	1.65 (1.00-2.90)
Mediterranean	Male	791	1.56 (1.19-2.07)**	1.24 (0.92-1.70)
Nordic	Female	376	1.50 (1.11-2.04)**	1.47 (1.00-2.19)
Nordic	Male	465	1.23 (0.94-1.62)	0.99 (0.73-1.35)
US	Female	1,555	2.12 (1.74-2.59)***	1.55 (1.25-1.92)***
US	Male	1,542	2.26 (1.87-2.74)***	1.54 (1.25-1.90)***
Western	Female	624	1.02 (0.81-1.29)	0.89 (0.66-1.21)
Western	Male	928	1.30 (1.07-1.59)**	1.04 (0.83-1.29)

Figure S3. Mortality Selection by Education Level



5. False discovery rate correction

Table S11. Multiple testing correction summary

Outcome	N Tests	Sig. (Raw)	Sig. (FDR)	Sig. (Bonferroni)
ADL	20	14	14	7
IADL	20	16	16	10
VM Decline	20	3	1	0

Table S12. Nagelkerke pseudo-R² (full model) by region, sex, and outcome

Region	Sex	ADL	IADL	Cognitive Decline
US	Female	0.174	0.184	0.058
Nordic	Female	0.183	0.281	0.027
Western	Female	0.162	0.223	0.027
Mediterranean	Female	0.242	0.300	0.020
Eastern	Female	0.145	0.286	0.022
US	Male	0.112	0.137	0.031
Nordic	Male	0.134	0.192	0.033
Western	Male	0.150	0.186	0.022
Mediterranean	Male	0.224	0.236	0.022
Eastern	Male	0.145	0.162	0.014

Table S13. Predicted probabilities (95% CI) by education level, healthy profile

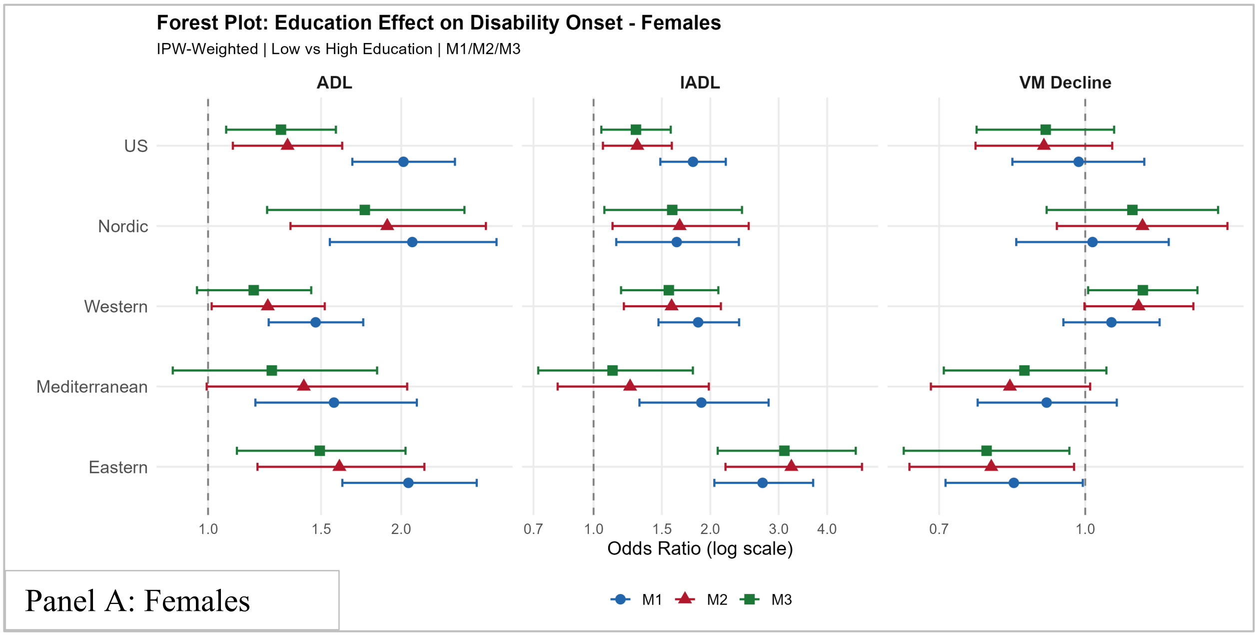
Region	Sex	ADL High	ADL Med	ADL Low	IADL High	IADL Med	IADL Low	VM.Decline_High	VM.Decline_Medium	VM.Decline_Low
US	Female	4.6 (3.7-5.4)	4 (3.3-4.7)	5.8 (4.7-7)	4.2 (3.4-5)	4.3 (3.6-5.1)	5.4 (4.3-6.5)	18.8 (16.7-20.8)	17.4 (15.6-19.2)	17.3 (14.9-19.8)
US	Male	4.5 (3.5-5.4)	4.9 (3.9-5.9)	6.1 (4.6-7.5)	2.9 (2.2-3.6)	4.5 (3.5-5.5)	6.5 (4.9-8.1)	21.6 (19.1-24)	19.1 (16.8-21.4)	20.6 (17.3-23.8)

Nordic	Female	1.5 (0.9-2)	2.4 (1.5-3.2)	2.5 (1.5-3.5)	0.6 (0.3-0.8)	0.8 (0.4-1.1)	0.9 (0.4-1.4)	20.5 (17.8-23.2)	17.5 (14.7-20.4)	22.5 (18.6-26.4)
Nordic	Male	2.8 (1.9-3.7)	3.1 (2.1-4.1)	3.9 (2.6-5.3)	0.8 (0.4-1.2)	0.9 (0.4-1.3)	1 (0.4-1.5)	18.8 (15.9-21.8)	21.2 (18-24.3)	20 (16.3-23.8)
Western	Female	3.2 (2.5-3.8)	2.8 (2.3-3.3)	3.7 (3-4.4)	1 (0.7-1.3)	0.7 (0.5-1)	1.6 (1.1-2)	21.3 (19.3-23.2)	21.9 (20.2-23.7)	23.7 (21.6-25.8)
Western	Male	3.2 (2.6-3.8)	3.3 (2.7-3.9)	3.4 (2.7-4.2)	0.7 (0.5-0.9)	0.9 (0.6-1.1)	1.5 (1-1.9)	20.6 (18.8-22.5)	20.1 (18.3-21.9)	20.5 (18.1-22.8)
Mediterranean	Female	1.7 (1.1-2.4)	1.9 (1.3-2.5)	2.2 (1.6-2.7)	1.2 (0.6-1.7)	0.5 (0.3-0.8)	1.3 (0.9-1.7)	23.2 (19.8-26.7)	20.3 (17.6-22.9)	20.7 (18.6-22.8)
Mediterranean	Male	2.4 (1.6-3.2)	1.9 (1.3-2.5)	2.3 (1.7-3)	0.9 (0.5-1.4)	0.6 (0.3-0.9)	1.2 (0.8-1.7)	22.9 (19.6-26.2)	20 (17.3-22.7)	22.8 (20.2-25.3)
Eastern	Female	2.7 (1.8-3.5)	2.9 (2.2-3.7)	4 (2.9-5)	0.7 (0.4-1)	0.9 (0.6-1.2)	2.1 (1.3-2.9)	20.9 (17.8-23.9)	18.4 (16.2-20.6)	17.1 (14.5-19.8)
Eastern	Male	2.6 (1.8-3.4)	3.1 (2.3-4)	3.3 (2.3-4.3)	1.3 (0.7-1.8)	2.1 (1.5-2.8)	2.5 (1.6-3.4)	22.3 (18.9-25.8)	21.3 (18.4-24.1)	21 (17.7-24.3)

Table S14. Predicted probabilities (95% CI), average covariate profile

region	sex	ADL_High	ADL_Medium	ADL_Low	IADL_High	IADL_Medium	IADL_Low	VM.Decline High	VM.Decline Medium	VM.Decline _Low
US	Female	5.1 (4.1-6.1)	4.5 (3.7-5.3)	6.5 (5.2-7.9)	5.7 (4.6-6.8)	5.8 (4.8-6.8)	7.2 (5.7-8.7)	17.1 (15-19.3)	15.9 (14-17.7)	15.8 (13.4-18.2)
US	Male	7 (5.6-8.4)	7.6 (6.3-9)	9.4 (7.4-11.4)	4.9 (3.7-6)	7.4 (6-8.7)	10.5 (8.3-12.8)	25.8 (22.8-28.9)	23 (20.5-25.5)	24.7 (21.2-28.2)
Nordic	Female	2.1 (1.4-2.8)	3.4 (2.3-4.4)	3.6 (2.3-4.8)	0.7 (0.4-1.1)	1 (0.6-1.5)	1.2 (0.6-1.7)	21 (18.2-23.7)	17.9 (15.2-20.6)	22.9 (19.1-26.8)
Nordic	Male	4.9 (3.5-6.3)	5.4 (4-6.9)	6.9 (4.9-8.8)	1 (0.5-1.5)	1.2 (0.6-1.7)	1.3 (0.7-2)	17.4 (14.7-20)	19.6 (16.8-22.4)	18.5 (15.2-21.8)
Western	Female	3.2 (2.5-3.8)	2.8 (2.3-3.3)	3.7 (3-4.4)	1 (0.7-1.3)	0.7 (0.5-1)	1.6 (1.1-2)	21.3 (19.3-23.2)	21.9 (20.2-23.7)	23.7 (21.6-25.8)
Western	Male	3.2 (2.6-3.8)	3.3 (2.7-3.9)	3.4 (2.7-4.2)	0.8 (0.6-1.1)	1 (0.7-1.3)	1.7 (1.2-2.2)	21.7 (19.8-23.6)	21.1 (19.4-22.9)	21.5 (19.2-23.8)
Mediterranean	Female	1.7 (1.1-2.4)	1.9 (1.3-2.5)	2.2 (1.6-2.7)	1.2 (0.6-1.7)	0.5 (0.3-0.8)	1.3 (0.9-1.7)	23.2 (19.8-26.7)	20.3 (17.6-22.9)	20.7 (18.6-22.8)
Mediterranean	Male	2.4 (1.6-3.2)	1.9 (1.4-2.5)	2.4 (1.8-3)	1.1 (0.6-1.6)	0.7 (0.4-1.1)	1.5 (1-2)	25.6 (22.2-28.9)	22.5 (19.7-25.2)	25.4 (22.9-28)
Eastern	Female	2.7 (1.8-3.5)	2.9 (2.2-3.7)	4 (2.9-5)	0.7 (0.4-1)	0.9 (0.6-1.2)	2.1 (1.3-2.9)	19.8 (16.4-23.1)	17.4 (15-19.9)	16.2 (13.5-19)
Eastern	Male	3.2 (2.2-4.1)	3.8 (2.9-4.7)	4 (3-5.1)	1.5 (0.9-2.1)	2.6 (1.8-3.3)	3 (2.1-4)	21 (17.4-24.5)	19.9 (17-22.8)	19.7 (16.4-22.9)

Figure S4. Forest plot of education effects (low vs. high), full model (95% CI)



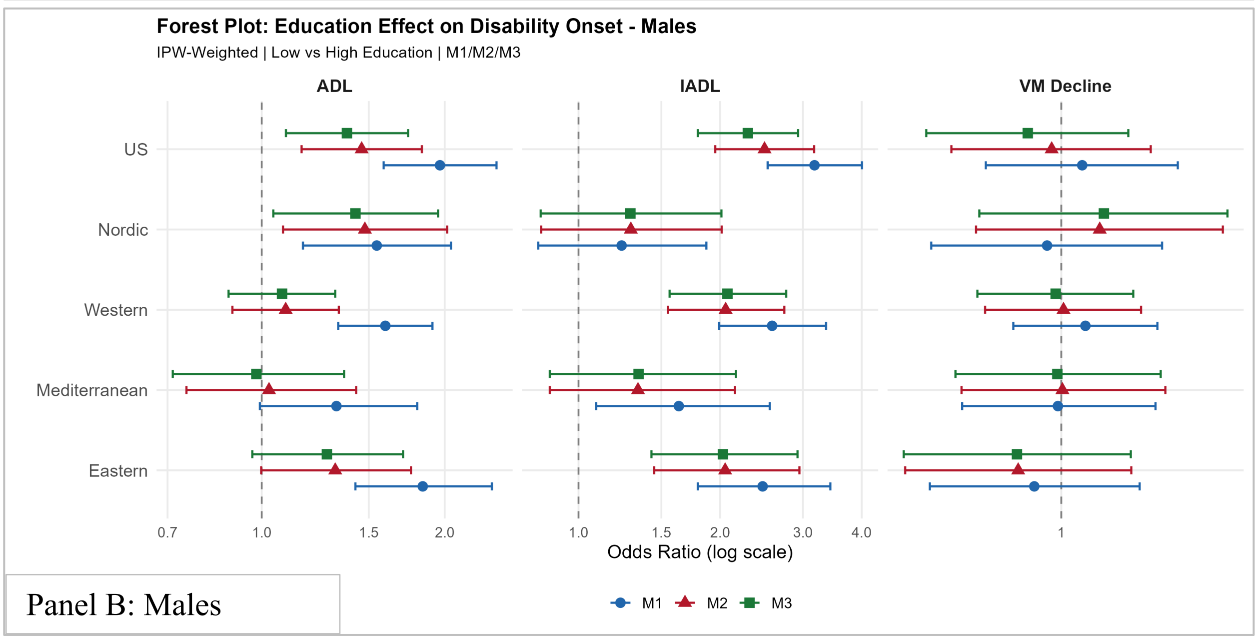


Figure S5. Predicted probabilities under average covariate profile, 95% CI