

Multilingualism protects against accelerated aging in cross-sectional and longitudinal analyses of 27 European countries

In the format provided by the
authors and unedited

Supplementary Note 1. Biobehavioral predictors

S1.1. Cognition

Cognition was assessed using a shortened version of the Mini-Mental State Examination (MMSE)¹, consisting of six components with a maximum total score of 20 points and a cut-off score of 13 points to indicate cognitive impairment. The assessment included the following components:

1. Participants provide the date (one point each for day, date, month, year).
2. Recall three objects named by the interviewer (one point each).
3. Perform three actions with a piece of paper (take it with the right hand, fold it in half, place it on the lap; one point each).
4. Recall the three objects (scored as in step 2).
5. Copy a drawing (one point if correct).
6. Recall a five-number sequence (one point per correct number, up to five points).

The final score was rescaled to a standard range (0–10), where higher scores indicate better cognitive performance.

S1.2. Functional ability

Functional ability was measured using a modified version of the Barthel Index², designed to assess a person's capacity to perform activities of daily living (ADLs). This version included 25 items covering physical mobility, self-care, instrumental activities, and environmental interaction. These include:

1. Do you have difficulty walking 100 meters?
2. Do you have difficulty sitting for about two hours?
3. Do you have difficulty getting up from a chair after sitting for long periods?
4. Do you have difficulty climbing several flights of stairs without resting?
5. Do you have difficulty climbing one flight of stairs without resting?
6. Do you have difficulty stooping, kneeling, or crouching?
7. Do you have difficulty reaching or extending your arms above shoulder level?
8. Do you have difficulty pulling or pushing large objects like a living room chair?
9. Do you have difficulty lifting or carrying weights over 10 pounds/5 kg, like a heavy bag of groceries?
10. Do you have difficulty picking up a small coin from a table?
11. Do you have difficulty dressing, including putting on shoes and socks?
12. Do you have difficulty walking across a room?
13. Do you have difficulty bathing or showering?
14. Do you have difficulty eating, such as cutting up your food?
15. Do you have difficulty getting in or out of bed?
16. Do you have difficulty using the toilet, including getting up or down?
17. Do you have difficulty using a map to figure out how to get around in a strange place?
18. Do you have difficulty preparing a hot meal?
19. Do you have difficulty shopping for groceries?
20. Do you have difficulty making telephone calls?
21. Do you have difficulty taking medications?
22. Do you have difficulty doing work around the house or garden?
23. Do you have difficulty managing money, such as paying bills and keeping track of expenses?
24. Do you have difficulty leaving the house independently and accessing transportation services?

25. Do you have difficulty doing personal laundry?

The final score for this domain was standardized to a scale ranging from 0 to 10, where 10 represents the highest level of functional ability.

S1.3. Well-being

SHARE included the Quality of Life Scale (CASP), which we used as a measure of wellbeing³. The final score for this domain was standardized by transforming the scores to a scale ranging from 0 to 10, where 10 represents the highest level of wellbeing.

S1.4. Education

Education level was assessed using the following questions:

0. No education.

1. Did not finish elementary school.

2. Finished elementary school (6th grade, 4th grade before the war).

3. Finished 7th or 8th grade of elementary school.

4. Completed secondary education.

5. Completed basic professional school.

6. Completed general secondary school without graduation certificate.

7. Technical high school without graduation diploma.

8. Specialized high school without secondary school certification.

9. General high school with graduation certificate.

10. Technical high school with graduation certificate.

11. Specialized high school with graduation certificate.

These categories were subsequently grouped into five educational levels: elementary school, middle school, high school, bachelor's degree, and postgraduate degrees.

S1.5. Physical activity

Physical (in)activity was assessed via the following questions: *"How often do you engage in activities that require a moderate level of energy such as gardening, cleaning the car, or doing a walk?"* and *"We would like to know about the type and amount of physical activity you do in your daily life. How often do you engage in vigorous physical activity, such as sports, heavy housework, or a job that involves physical labour?"* Both questions had as possible answers: 'More than once a week', 'Once a week', 'One to three times a month' and 'Hardly ever, or never'.

We transformed it into a categorical variable indicating whether participants engage in physical activity or not.

S1.6. Hypertension

Hypertension was assessed through the self-reported question: *"Has a doctor ever told you that you had high blood pressure or hypertension?"* Responses were transformed into a binary categorical variable indicating whether participants had been diagnosed with high blood pressure or not.

S1.7. Diabetes

Diabetes was assessed through the self-reported question: *“Has a doctor ever told you that you had diabetes or high blood sugar?”* Responses were transformed into a binary categorical variable indicating whether participants had been diagnosed with diabetes or high blood sugar or not.

S1.8. Heart Disease

Heart disease was assessed through the self-reported question: *“Has a doctor ever told you that you had a heart attack, including myocardial infarction, coronary thrombosis, or any other heart problem, including congestive heart failure?”* Responses were transformed into a binary categorical variable indicating whether participants had been diagnosed with heart disease or not.

S1.9. Visual impairment

Visual impairment was assessed using two self-reported questions: *“How good is your eyesight for seeing things at a distance, like recognizing a friend across the street?”* and *“How good is your eyesight for seeing things up close, like reading ordinary newspaper print?”* Responses were categorized on a five-point scale: excellent, very good, good, fair, and poor.

S1.10. Hearing impairment

Hearing impairment was assessed through the self-reported question: *“Is your hearing excellent, very good, good, fair, or poor?”* Responses were categorized accordingly into five levels: excellent, very good, good, fair, and poor.

S1.11. Unhealthy weigh

Participants were asked whether they had ever been diagnosed with obesity, underweight, or other weight-related disorders. Responses were used to indicate the presence or absence of unhealthy weight conditions.

S1.12. Alcohol consumption

Alcohol consumption was assessed based on participants' self-reported drinking frequency, using the following response options: “Daily or almost daily,” “Five or six times per week,” “Three or four times per week,” “Once or twice per week,” “Once or twice per month,” “Less than once per month,” and “Not even once in the past 3 months.” Based on these responses, alcohol consumption was categorized into four levels: never consumed, normal consumption, excessive consumption, and severe consumption.

S1.13. Sleep problems

Sleep problems were assessed with the question: *“Do you use medications for sleeping difficulties?”* Based on responses, the variable was categorized into two levels, indicating whether or not participants experienced sleep problems.

Supplementary Tables

Supplementary Table 1. Demographic information for SHARE dataset.

(N = 86,149; 39,034 female participants, mean age = 66.55, SD = 9.91)			
Country	Age (SD)	Age (range)	N total (female participants)
Austria	67.26 (9.67)	(51, 90)	4320 (1873)
Belgium	63.68 (10.4)	(51, 90)	4942 (2309)
Bulgaria	67.61 (9.48)	(51, 90)	1953 (834)
Croatia	65.45 (9.0)	(51, 90)	2798 (1270)
Cyprus	69.87 (10.0)	(51, 90)	1205 (508)
Czechia	67.66 (9.37)	(51, 90)	5575 (2418)
Denmark	63.66 (9.96)	(51, 90)	2609 (1263)
Estonia	68.31 (10.48)	(51, 90)	7522 (3162)
Finland	67.21 (9.39)	(51, 90)	1982 (925)
France	65.74 (10.6)	(51, 90)	3640 (1674)
Germany	66.42 (9.83)	(51, 90)	4567 (2198)
Greece	64.95 (10.29)	(51, 90)	2599 (1179)
Hungary	66.8 (9.13)	(51, 90)	3010 (1324)
Italy	64.97 (9.75)	(51, 90)	4541 (2138)
Latvia	67.84 (10.01)	(51, 90)	1684 (640)
Lithuania	67.57 (10.26)	(51, 90)	2033 (763)
Luxembourg	66.11 (9.56)	(51, 90)	2104 (985)
Malta	68.13 (8.77)	(51, 90)	1259 (569)
Netherlands	65.95 (9.72)	(51, 90)	2546 (1176)
Poland	64.74 (9.49)	(51, 90)	3612 (1697)
Portugal	64.72 (9.0)	(51, 90)	1914 (912)
Romania	66.66 (9.15)	(51, 90)	2083 (913)
S. Republic	63.1 (8.02)	(51, 90)	2022 (954)
Slovenia	67.82 (9.76)	(51, 90)	5291 (2383)
Spain	67.77 (10.43)	(51, 90)	4912 (2374)
Sweden	69.07 (9.22)	(51, 90)	2792 (1342)
Switzerland	67.56 (9.69)	(51, 90)	2634 (1251)

Supplementary Table 2. Performance metrics across training, validation, and test datasets.

Dataset	R ²	F ²	r	RMSE	MDE	MAE
Train	0.26 (0.001)	0.34 (0.002)	0.51 (0.001)	8.54 (0.01)	0.03 (0.001)	7.00 (0.008)
Validation	0.24 (0.008)	0.31 (0.014)	0.49 (0.008)	8.65 (0.086)	0.03 (0.015)	7.09 (0.072)
Test	0.26 (0.001)	0.36 (0.002)	0.52 (0.001)	8.51 (0.005)	0.07 (0.003)	6.99 (0.004)

Supplementary Table 3. Stratified analysis by age group in the cross-sectional study. Odds ratios (OR) from the cross-sectional analysis, estimated using logistic regression models. Two-sided Wald z tests were used to derive exact p-values and 95% confidence intervals.

Monolingual				
Age ranges	OR	95% CI	z	p-value
51–64	1.30	1.24 – 1.36	10.98	1.0e-15
65–77	1.62	1.54 – 1.71	17.76	1.0e-15

78–90	1.70	1.59 – 1.82	15.64	1.0e-15
1 additional language				
Age ranges	OR	95% CI	z	p-value
51–64	0.79	0.74 – 0.84	-7.74	1.0e-14
65–77	0.92	0.86 – 0.99	-2.17	3.0e-02
78–90	1.03	0.94 – 1.13	0.55	5.9e-01
2 additional languages				
Age ranges	OR	95% CI	z	p-value
51–64	0.81	0.77 – 0.86	-6.9	5.3e-12
65–77	0.63	0.58 – 0.67	-13.01	1.0e-15
78–90	0.57	0.52 – 0.62	-12.37	1.0e-15
3 additional languages				
Age ranges	OR	95% CI	z	p-value
51–64	0.96	0.91 – 1.02	-1.22	2.2e-01
65–77	0.69	0.64 – 0.74	-9.99	1.0e-15
78–90	0.60	0.55 – 0.66	-10.19	1.0e-15
Total (≥ 1 language)				
Age ranges	OR	95% CI	z	p-value
51–64	0.77	0.73 – 0.81	-10.97	1.0e-15
65–77	0.62	0.59 – 0.65	-17.75	1.0e-15
78–90	0.59	0.55 – 0.63	-15.64	1.0e-15

Supplementary Table 4. Stratified analysis by age group in the longitudinal study. Relative risks (RR) from the longitudinal analysis, estimated using log-binomial generalized linear models. Two-sided Wald z tests were used to derive exact p-values and 95% confidence intervals.

Monolingual				
Age ranges	RR	95% CI	z	p-value
51–64	1.33	1.27 – 1.40	11.14	1.0e-15
65–77	1.56	1.47 – 1.65	15.25	1.0e-15
78–90	1.60	1.49 – 1.72	12.70	1.0e-15
1 additional language				
Age ranges	RR	95% CI	z	p-value
51–64	0.86	0.81 – 0.92	-4.56	5.0e-06
65–77	0.90	0.83 – 0.97	-2.65	8.1e-03
78–90	1.08	0.97 – 1.19	1.42	1.5e-01
2 additional languages				
Age ranges	RR	95% CI	z	p-value
51–64	0.85	0.80 – 0.89	-6.18	6.5e-10
65–77	0.74	0.70 – 0.79	-9.31	1.0e-15
78–90	0.69	0.64 – 0.75	-9.16	1.0e-15
3 additional languages				
Age ranges	RR	95% CI	z	p-value
51–64	0.82	0.76 – 0.88	-5.68	1.4e-08
65–77	0.59	0.54 – 0.65	-11.15	1.0e-15
78–90	0.50	0.44 – 0.57	-11.05	1.0e-15
Total (≥ 1 language)				
Age ranges	RR	95% CI	z	p-value
51–64	0.75	0.71 – 0.79	-11.15	1.0e-15
65–77	0.64	0.61 – 0.68	-15.26	1.0e-15
78–90	0.62	0.58 – 0.67	-12.72	1.0e-15

Supplementary Table 5. Results from calibration tests. Calibration analyses using the Hosmer–Lemeshow goodness-of-fit test with bootstrapped confidence intervals (1,000 iterations). A good model fit is indicated by $p > 0.05$

Outcome	p value (10 groups)	p value (50 groups)	OR	CI 99%	OR (min - max)
Monolingual	0.151	0.269	2.128	2.123	2.133
1 additional language	0.096	0.232	0.755	0.753	0.757
2 additional languages	0.165	0.308	0.535	0.533	0.536
3 additional languages	0.126	0.315	0.663	0.662	0.665
Total (≥ 1 language)	0.145	0.268	0.470	0.469	0.471

Supplementary Table 6. Country-level percentages of self-reported language skills from the Eurostat database in the four waves. Values within () indicate missing and interpolated data from the two adjacent years.

	Monolinguals				1 additional language				2 additional languages				3 or + additional languages			
Country	2007	2011	2016	2022	2007	2011	2016	2022	2007	2011	2016	2022	2007	2011	2016	2022
Austria	20.3	22	14	12	50.4	50.5	49.6	53	20.2	18.9	23.3	24.6	9.1	8.8	13.4	10.8
Belgium	32.1	42	22	22	16.3	13.8	18.2	25.1	26.1	23.5	33.5	29.5	25.4	20.6	26.9	23.5
Bulgaria	44.1	61	51	52	30	24.4	32.5	34.5	21.2	11.7	13.7	11.2	4.7	2.8	3.3	2.5
Croatia	31.4	(30.5)	27	21	39.7	(40.8)	45.2	50.3	21.3	(21.4)	21.8	23.2	7.6	(7.32)	6.2	5.8
Cyprus	14.6	16	11	8.1	59.3	56.7	62.2	61.5	17.9	19.2	20.3	21.2	8.1	8	7	9.2
Czechia	31.9	31	21	22	34.6	39.6	44.7	46.6	24.7	22.4	26.9	24.5	8.8	7.1	7.4	6.8
Denmark	12	5.9	4.2	9.8	35.8	26.3	29.9	29.2	38.5	43.1	41.2	33	13.6	24.7	24.6	28.1
Estonia	13.6	15	8.8	4.5	30.4	24.1	26.4	19.3	35.3	35.1	39.1	43.2	20.6	26.3	25.7	33
Finland	16.1	8.2	8	7.8	16	13.1	15.6	20.5	29.9	29.5	31.6	33.5	38	49.2	44.9	38.1
France	41.2	41	40	23	35.9	34.9	35.4	34.5	18.4	19.2	20.1	29.8	4.5	4.6	4.6	13.1
Germany	28.6	22	21	12	41.3	41.9	41.7	41.4	21.5	26.3	26.6	29.8	8.7	10.3	10.4	16.6
Greece	43.4	42	34	29	44.8	43	48.5	55	9.9	12.2	15.3	13.1	2	3	2.7	3.1
Hungary	74.8	63	58	51	17.6	25.9	28.6	30.6	6.3	9.2	11.1	14.2	1.3	1.7	2.7	3.8
Italy	38.6	40	34	32	33.8	39.6	41.6	37.5	20.9	16.6	20.1	22.8	6.7	3.7	4.4	7.6
Latvia	5.1	5.1	4.2	5	40	35.7	33.7	26.4	42.9	46.1	49.3	52.6	12	13.1	12.7	16
Lithuania	2.5	2.7	4.5	4.6	31.5	40.7	42.9	38.3	45.8	44.7	39	47.7	20.3	11.9	13.7	9.3
Luxembourg	(1.0)	1.1	5.5	5.5	(4.9)	5	16.2	17.3	(21)	22	27.1	23.1	(72)	72	51.2	54.1
Malta	8.3	11	8.2	20	26	24.7	32.4	47.2	42.8	45.7	43.2	24.5	22.8	18.6	16.2	7.9
Netherlands	(13.9)	14	14	7	(25.2)	25.2	28.7	20.7	(37)	37.1	37.1	32	(23.8)	23.7	20.6	40.2
Poland	37.3	38	33	27	39	38.7	45	47.4	19.6	19.2	19.2	20.5	4.1	4	2.8	5
Portugal	51.3	42	31	30	22.3	26.6	28.9	31	17.5	20.5	24.8	25	8.9	11.5	15.3	14
Romania	69.6	(68.5)	64	51	19.2	(20.3)	24.7	35.2	9.9	(9.96)	10.2	12.3	1.3	(1.22)	0.9	1.2
Serbia	(37.4)	37	21	12	(47.4)	47.4	37.2	55.8	(12.23)	12.3	21.6	25.3	(2.8)	2.9	20.5	6.9
Slovenia	7.7	7.6	16	4	20.5	15	20.7	16.6	37.2	32.6	25.7	23.1	34.6	44.9	37.7	56.3
Spain	46.6	49	46	44	35.4	34	34.8	34.6	13.6	12.6	14.3	15.8	4.3	4.5	5.2	5.8
Sweden	5	8.2	3.4	4.1	44.6	31.6	45.9	50.8	31	29.7	31.7	32.3	19.4	30.5	19	12.7
Switzerland	(11.34)	12	8.3	(8.3)	(20.7)	20.9	19.7	(19.7)	(34.46)	34.2	35.5	(35.5)	(33.6)	32.9	36.5	(34.6)

Supplementary References

1. Folstein, M.F., Folstein, S.E. & McHugh, P.R. "Mini-mental state". A practical method for grading the cognitive state of patients for the clinician. *Journal of psychiatric research* **12**, 189-198 (1975).
2. Mahoney, F.I. & Barthel, D.W. Functional Evaluation: The Barthel Index. *Maryland state medical journal* **14**, 61-65 (1965).

3. Hyde, M., Wiggins, R.D., Higgs, P. & Blane, D.B. A measure of quality of life in early old age: the theory, development and properties of a needs satisfaction model (CASP-19). *Aging Ment Health* 7, 186-194 (2003).