Cognitive function explains the association between academic education and increased physical activity

For correspondence:
boris.cheval@unige.ch

Boris Cheval[1,2*], Ilyes Saoudi[3], Silvio Maltagliati[3], Layan Fessler[3], Ata Farajzadeh[4,5], Stefan Sieber[6], Stéphane Cullati,[7,8] Matthieu P. Boisgontier[4,5]

[1]Swiss Center for Affective Sciences, University of Geneva, Switzerland. [2]Laboratory for the Study of Emotion Elicitation and Expression (E3Lab), Department of Psychology, University of Geneva, Switzerland. [3]Univ. Grenoble Alpes, SENS, F-38000 Grenoble, France. [4]School of Rehabilitation Sciences, Faculty of Health Sciences, University of Ottawa, Ontario, Canada. [5]Bruyère Research Institute, Ottawa, Ontario, Canada. [6]LIVES Centre, Swiss Centre of Expertise in Life Course Research, University of Lausanne, Switzerland. [7]Population Health Laboratory, University of Fribourg, Switzerland. [8]Department of Readaptation and Geriatrics, University of Geneva, Switzerland. [*]Corresponding author: Campus, Biotech, Chemin des Mines 9, 1202 Genève, Switzerland; boris.cheval@unige.ch

Please cite as: Cheval, B., Saoudi, I., Maltagliati, S., Fessler, L., Farajzadeh, A., Sieber, S., Cullati, S., Boisgontier, M.P. (2022). Cognitive function explains the association between academic education and increased physical activity. *SportRxiv*. DOI: 10.51224/SRXIV.151

Abstract

Background: A higher level of academic education is associated with higher levels of physical activity across the life course. However, the mechanisms underlying this association remain unclear. Cognitive functioning is a potential mediator of this association, as higher levels of education are associated with better cognitive function, which is associated with greater engagement in physical activity. Therefore, this study aimed to investigate whether cognitive function mediates the relationship between education and physical activity.
Methods: We used large-scale longitudinal data from 96,990 adults 50 years of age or older (54% women) from the Survey of Health, Ageing and Retirement in Europe (SHARE). Education and physical activity were self-reported. Two indicators of cognitive function including delayed recall and verbal fluency were measured using cognitive tests. All measures were collected seven times between 2004 and 2019. The mediating role of cognitive function was tested using multilevel mediation analyses.
Results: Higher levels of education were associated with better cognitive function, which was associated with higher physical activity, demonstrating an indirect effect of education on physical activity through cognitive function. Cognitive function explained 91.6% of the total effect of education on physical activity. Moreover, education was no longer significantly associated with physical activity after adjustment for cognitive function.
Conclusions: These findings suggest that cognitive function mediates the association between education and physical activity. This study provides new evidence for the beneficial role of education and cognitive function in regulating physical activity in older adults.

Keywords: Educational status, cognition, exercise, aging, longitudinal studies

Introduction

Educational attainment plays a crucial role in promoting the engagement in multiple health behaviors,[1-4] such as physical activity.[5-8] Less educated people exhibit a higher risk of physical inactivity, a risk that increases with age.[6,8-10] Moreover, a recent Mendelian randomization study conducted on middle-age Finnish adults revealed that a higher level of education was associated with more time spent on physical activity.[5] Overall, these findings support the role of education in determining physical activity levels and their maintenance across the life course. Still, gaps remain in our understanding of the mechanisms underpinning this association.

Several mechanisms may explain why lower levels of education lead to a less physically active lifestyle. Firstly, poor health literacy has been suggested to explain the relationship between lower education and lower engagement in protective health behaviors.[11-15] Secondly, less-educated people may have developed weaker motivation and self-efficacy toward health-protective behaviors, putting them at higher risk for disengagement from these behaviors.[16-19] Thirdly, because the place of residence is influenced by sociocultural position,[20] less-educated people are more likely to live in disadvantaged physical (e.g., poor-maintained facilities, lack of aesthetic and natural spaces) and social environments (e.g., unsafe and isolated areas), which could contribute to their lack of engagement in physical activity.[21-23]

In addition to these mechanisms, cognitive function is a potential candidate to mediate the association between education and physical activity. On the one hand, previous studies and meta-analyses showed that higher levels of education were associated with better cognitive function.[24-29] On the other hand, studies showed that better cognitive function predicted higher engagement in physical activity.[30-34] Conceptually, according to the Theory of Effort Minimization in Physical Activity (TEMPA),[35] this latter association is explained by the fact that cognitive function is considered necessary to counteract the innate human attraction to effort minimization.[35-40] In line with this view and consistent with epidemiological and neurobehavioral evidence, experimental studies have demonstrated that cognitive function is crucial in inhibiting this automatic attraction to physical inactivity and in promoting regular engagement in physical activity.[41-43] In sum, the above literature suggests that cognitive function underlies the association between education and physical activity. However, to the best of our knowledge, no study has directly investigated this potential mediation.

The objective of the present study was to examine whether cognitive function mediates the relationship between education and physical activity in adults 50 years of age or older. Based on the previous literature, we hypothesized that higher cognitive function explains the positive relationship between and physical activity.

Methods

Participants and study design

Data were drawn from the Survey of Health, Ageing and Retirement in Europe (SHARE), a longitudinal population-based study of adults 50 years of age or older living in 27 European countries and one middle east country.[44] Data were collected every two years between 2004 and 2019, with a total of eight measurement waves using computer-assisted personal interviews (CAPI) in participants' homes. Physical activity and cognitive function (delayed recall and verbal fluency) were assessed in all measurement waves except wave 3 (2008-2009). Education level was measured when participants were first included in the study. The SHARE study was approved by the relevant research ethics committees in the participating countries, and all participants provided written informed consent. To be included in the study, participants must have at least one measure of physical activity, one measure of cognitive function, and indicated their education level. We excluded individuals with suspected dementia at baseline, as indicated by a score above two on the time-orientation question,[28] and people who reported more than two limitations in activities of daily living (ADL) at baseline.

Measures

Outcome: Physical activity

Physical activity was derived from the following two questions: "How often do you engage in activities that require a low or moderate level of energy such as gardening, cleaning the car, or going for a walk?" and "How often do you engage in vigorous physical activity, such as sports, heavy housework, or a job that involves physical labor?".[21,31,45,46] Participants responded using a four-point scale: 1 = more than once a week; 2 = once a week; 3 = one to three times a month; 4 = hardly ever or never. Participants who did not respond "more than once a week" to any item were classified as physically inactive. As described in previous research,[7,8,46] this strategy reduces the potential misclassification bias that would lead to misclassifying physically inactive participants as physically active.

Independent variable: Education

The level of education was based on the UNESCO's International Standard Classification of Education (ISCED),[47] and participants were defined as having a high level of education (ISCED levels 5 and 6, indicating tertiary education) or a low level of education (ISCED levels 0 to 4, indicating primary or secondary education).[48]

Mediating variables: Cognitive function

Cognitive function was assessed using two indicators including delayed recall and verbal fluency. Delayed recall is a reliable predictive measure of the development of dementia.[49,50] Delayed recall was extracted from an adapted 10-word delayed recall test.[51] First, participants listened to a list of 10 words that were read out loud by the interviewer. Then, they were immediately asked to recall as many words as possible. At the end of the cognitive testing session, the participants were asked to recall the words from the list a second time, which captured a delayed recall score. This score ranged from 0 to 10, with higher scores indicating a better cognitive function. In the verbal fluency test,[52] the interviewer asked participants to name as many different animals as they could think of in one minute. The score was the total number of correctly named animals, with a higher score indicating better performance.

Covariates and potential confounders. We conducted a directed acyclic graph (DAG) to identify potential confounding variables.[53,54] Specifically, the following variables were included: age group (50-64, 65-79, 80-96 years), birth cohort [war (1914-1918, 1939-1945), great depression (1929-1938), no war nor economic crisis (before 1913, 1919-1928, after 1945)], sex (male, female), and country of residence.

Statistical analysis

The mediating role of cognitive function on the association between education and physical activity was analyzed using mixed-effects models, which account for the nested structure of the data (i.e., repeated measurement over time within a single participant) and provide acceptable Type I error rates.[55] The random structure included a random intercept for participants and a random linear slope of measurement wave (1 to 8) for participants. This latter random effect enabled the model to consider that each participant could have their own evolution of cognitive function and physical activity across time. Including these random effects in the models favors a correct estimation of fixed effects and of significance (i.e., *p*-values), despite the dependency between observations for a same individual.

Consistent with previous literature,[56,57] we relied on two complementary approaches to test the mediation process. First, the distribution-of-the-product coefficients approach was conducted using the RMediation package.[58] This approach provides confidence intervals around the indirect effects using a bootstrap method. Second, we tested the parameters of the individual models to confirm the significance of the indirect pathway using the component approach.[59] This approach tests each component of the indirect effect (i.e., from the independent variable to the mediator [the first component] and from the mediator to the outcome [the second component]) (Figure 1) and refers to the causal steps test,[60] or the joint-significant test.[61] In comparison with sole reliance on a bootstrapped approach, the component approach provides decreased risks of Type I errors.[59]

Two mixed-effects models were computed to investigate the mediating role of cognitive function on the relationship between education and physical activity. The first linear model (Model 1) tested the association between education and cognitive function (i.e., *a* path, from exposure to mediator), after adjusting for confounders. The second logistic model (Model 2) tested the association between cognitive function and physical activity (i.e., *b* path, from mediator to outcome), after adjusting for confounders and education. Note that in Model 2, both indicators of cognitive function were included at the same time to examine the association between a given indicator of cognitive function and physical activity, above and beyond the effect of the second indicator. In the distribution-of-the-product method of the Rmediation package, an indirect effect is assumed when the 95% confidence interval around the indirect effect does not include zero. In the component approach, an indirect effect is evidenced if both the association between education and cognitive function (i.e., *a* path, Model 1) and the association between cognitive function and physical activity (i.e., *b* path, Model 2) are significant. The proportion of the total effect explained by the mediating variable was calculated by subtracting the direct effect (*c*' path) from the total effect (*c* path), and then dividing this result by the total effect (i.e., [total effect - direct effect] / total effect). Estimates of the effect size for fixed effects were reported using the marginal and conditional pseudo-R^2 computed with the MuMin R package.[62]

Sensitivity analyses

Two sensitivity analyses were conducted. The first sensitivity analysis excluded participants who dropped out during the survey (i.e., participants who responded to neither wave 7 nor wave 8). The second sensitivity analysis excluded participants who died during the survey.

Robustness analysis

We conducted a robustness analysis in which a time lag was created between cognitive function (i.e., the mediator) and physical activity (i.e., the outcome). Accordingly, in line with previous literature,[63] for a given wave (with the exception of wave 1), cognitive function was assigned the score of the preceding wave. This approach was intended to reduce a potential reverse causation bias on the observed associations.

Results

Descriptive results

A total of 96,990 participants (54.3% women) were included in the sample. Table 1 presents the characteristics of the participants stratified by education level. Simple association tests showed that participants with higher levels of education had better cognitive function, were more physically active, younger, and more likely to be a man (*ps* < .001).

Table 1. Baseline characteristics of the participants across the level of education

N = 96,990	Low education (N = 75,278)	High education (N = 21,712)	*p*-value
Outcome: Physical activity			
Physically inactive, n (%)	20126 (26.7)	4570 (21.0)	
Physically active, n (%)	55152 (73.3)	17142 (79.0)	<.001
Mediator: Cognitive function			
Delayed recall, mean ± SD	2.7 ± 1.3	3.4 ± 1.0	<.001
Verbal fluency, mean ± SD	18.9 ± 7.3	23.5 ± 7.7	<.001
Other covariates			
Age, n (%)			
50-64	42514 (56.5)	14452 (66.6)	
65-79	27718 (36.8)	6403 (29.5)	
80-96	5046 (6.7)	857 (3.9)	<.001
Gender			
Women, n (%)	41799 (55.5)	10919 (50.3)	
Men, n (%)	33479 (44.5)	10793 (49.7)	<.001
Birth Cohort, n (%)			
After 1945	40905 (54.3)	14298 (65.8)	
Between 1939 and 1945	15296 (20.3)	3985 (18.4)	
Between 1929 and 1938	14494 (19.3)	2729 (12.6)	
Between 1919 and 1928	4583 (6.1)	700 (3.2)	<.001

Note. Baseline = first measurement for each participant; SD = standard deviation; High education = tertiary education; Low education = no tertiary education; *p*-values are based on the analysis of variance and chi-square tests for continuous and categorical variables, respectively, testing the effect of physical activity at baseline (physically active vs. physically inactive) on these variables.

Main analyses

Results of the mediation analysis based on the distribution-of-the-product approach showed a significant indirect effect of education on physical activity through both verbal fluency (b = 0.16, 95% confidence interval [95% CI] = 0.15–0.17) and delayed recall (b = 0.04, 95% CI = 0.04–0.05) (Table 2).

Table 2. Results of the distribution-of-the-product coefficients approach

(N = 96,990)	**b (95% CI)**
Mediators	
Delayed recall	0.044 (0.039;0.050)
Verbal fluency	0.161 (0.153;0.170)
Proportion of mediated effect	91.6%

Note. 95% CI = confidence interval at 95%. An indirect effect is assumed when the 95% confidence interval around the indirect effect does not include zero.

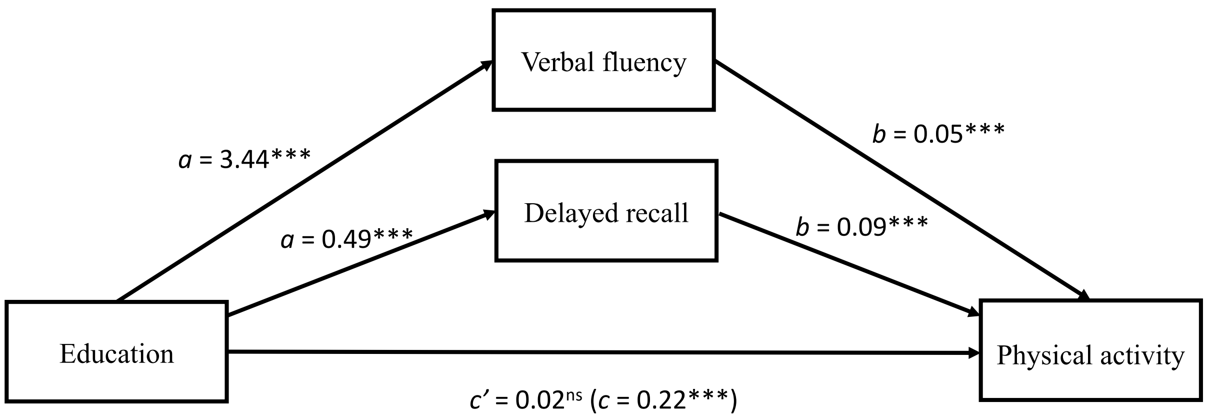
Results of the mediation analysis based on the component approach (Table 3) showed that, in Model 1, individuals with a high (vs. low) education had better cognitive function (b = 3.44, 95% CI = 3.35–3.53, $p < .001$; b = 0.49, 95% CI = 0.48–0.51, for verbal fluency and delayed recall, respectively). In Model 2, results showed that better cognitive function was associated with higher odds of being physically active (vs. inactive) (b = 0.05, odds ratio [OR] = 1.05, 95% CI = 1.04–1.05, $p < .001$; b = 0.09, OR = 1.09, 95% CI = 1.08–1.11, for verbal fluency and delayed recall, respectively). Because the two components of the mediation were significant for both indicators of the cognitive function, these results were consistent with the results of the mediation analysis based on the distribution-of-the-product method and supported a significant indirect effect of education on physical activity through cognitive function. Further, in Model 2, after adjusting for cognitive function (i.e., both delayed recall and verbal fluency), results showed that the association between education and physical activity was not significant (b = 0.02, OR = 1.02, 95% CI = 0.98–1.06, $p = .323$), suggesting that the association of education with physical activity was fully mediated by cognitive function. Note that the effect of education on physical activity when cognitive function was not adjusted in the models was equal to b = 0.22 (OR = 1.24; 95% CI = 1.20–1.29, p < .001). Thus, the proportion of the total effect of education on physical activity that was mediated by cognitive function was 91.6%. Model 2 explained 13.6% of the marginal variance and 39.8% of the conditional variance in physical activity.

Table 3. Results of the component approach

(N = 96,990)	**Model 1 Cognitive function**				**Model 2 Physical activity**	
Predictors:	**Delayed recall**		**Verbal fluency**			
	b (CI)	***p***	**b (95% CI)**	***p***	**[b] OR (95% CI)**	***p***
Education (ref. Low)	0.49 (0.48;0.51)	<.001	3.44 (3.35;3.53)	<.001	[.02] 1.02 (0.98;1.06)	.323
Cognitive function						
Delayed recall	-	-	-	-	[.09] 1.09 (1.08;1.11)	<.001
Verbal fluency	-	-	-	-	[.05] 1.05 (1.04;1.05)	<.001

Note. 95% CI = confidence interval at 95%; OR = Odds Ratio. Results are derived from mixed-effects models. Results of Model 1 are derived from linear mixed-effects models, whereas results of Model 2 are derived from logistic mixed-effects models. The coefficients estimating the association between education and cognitive function were obtained using two separated models (i.e., one model estimating the association between education and verbal fluency, and a second model estimating the association between education and delayed recall), whereas the coefficients estimating the associations between the cognitive function and physical activity were obtained with a single model including both cognitive function at once. The latter model allowed examining the specific contribution of each cognitive function on physical activity. Models were adjusted for wave of measurement (fixed and random), age, sex, birth cohort, and country of residence.

Figure 1. Mediation model.



Note. ***: p < .001; c = total effect; c' = direct effect; a = path Model 1; b = path Model 2.

Sensitivity and robustness analyses

The sensitivity (supplemental table S1 and S2) and the robustness analyses (supplemental table S3) yielded consistent results to the main analyses. Specifically, we found a significant indirect effect of education on physical activity through both cognitive functions. Note that for the robustness analysis, which has introduced a time lag between cognitive function and physical activity, the proportion of the mediated effect was lower relative to the proportion observed in the main analysis (i.e., 55.8% vs. 91.6%). Moreover, in this robustness analysis, education remained significantly associated with physical after adjustment for cognitive function.

Discussion

Main findings

This large-scale study of European adults aged 50 years or older revealed that the association between education level and physical activity behavior was explained by cognitive function: higher educational level was associated with increased cognitive function, which in turn promoted higher physical activity. Education level was no longer significantly associated with physical activity after adjustment for cognitive function, suggesting that cognitive function explained the protective role of high education level on physical activity. In this section, we discuss our results in the context of previous literature, elaborate on the mechanisms likely to explain the observed associations, and we provide some limiting conditions to these findings.

Comparison with previous studies

Our results showed an association between education and physical activity that is consistent with earlier evidence indicating that individuals with a higher level of education are more likely to engage in a wide range of health-protective behaviors,[1-4] including physical activity.[5-8] The role of education in promoting a sustained engagement in health behaviors can be explained by several mechanisms, including, but not limited to, increased knowledge of the health recommendations (i.e., health literacy),[11-14] a greater motivation or ability to engage in protective health behaviors,[16-18] as well as better physical and social conditions.[20-23] Here, we demonstrate, for the first time, that this association could be underpinned by improved cognitive function. But how this mediating effect of cognitive function on the relationship between education and physical activity be explained?

Potential mechanisms

On the one hand, our results showing that higher educational level was associated with better cognitive function are aligned with previous literature.[24-28] The mechanism of cognitive reserve can be put forward to explain how education enhances cognitive function.[25,48,64,65] Originally, cognitive reserve was developed to explain the gap between biological damage in the brain (or brain pathology) and patient's clinical presentation.[64] Recently, the relevance of cognitive reserve has been extended to physiological cognitive aging.[65] Cognitive reserve is the brain's ability to optimize its performance through differential recruitment of brain networks, which may be associated with different cognitive strategies.[64] The construction of cognitive reserve is based on cognitively stimulating situations, such as academic, occupational, and leisure activities. [29,65] Particularly, Lenehan et al. (2015),[25] contends that empirical data supports the proposition that more educated individuals maintain a higher level of cognitive functioning compared with less educated individuals. On the other hand, we found that higher cognitive function was associated with higher physical activity. This result is consistent with previous studies suggesting that cognitive function is required to engage in physical activity.[30-34] The recent Theory of Effort Minimization in Physical Activity (TEMPA) allows to account for these findings.[35]

Anchored in an evolutionary perspective, TEMPA posits that humans have an innate attraction to physical effort minimization,[35,37,39,40,66] and that engaging in physically active behaviors requires higher levels of cognitive function to overcome this attraction.[31,41,43,66] This hypothesis is supported by the current results showing that education has an indirect effect on physical activity through an effect on cognitive function. Specifically, in the main analyses, cognitive function explained 91.6% of the total effect of education on physical activity. Importantly, education was no longer significantly associated with physical activity after adjustment for cognitive function, suggesting that cognitive function largely explained the positive association between an educational attainment and physical activity. However, it should be noted that the proportion of mediated effect was lower in the sensitivity and robustness analyses, with education remaining significantly associated with physical activity after adjustment for cognitive function. Nevertheless, these findings suggest that, among the multiple potential mechanisms that have been shown to underpin the association between education level and physical activity (i.e., health knowledge, motivation, environmental/neighborhood conditions), cognitive function may play a prominent role. To our knowledge, this study is the first to demonstrate this mediating pathway.

Limitations and strengths

The study includes at least three limitations. First, we relied on a self-reported measure of physical activity. This measure may have reduced measurement validity and could have generated a misclassification bias.[67] Likewise, this measure was subject to a lack of granularity because it only assessed the participation in low-light-moderate and vigorous physical activity. Accelerometer-measured physical activity should be included in future studies. Second, our measure of cognitive function was based on two tests intended to capture two dimensions of cognitive function, namely cognitive impairment and early signs of dementia.[49,51,52] Yet, general cognitive function is underpinned by many other cognitive domains such as problem solving, reasoning, processing speed, and inhibition.[68,69] Since both the effect of education and cognitive function could differ by cognitive dimension,[21,35,36,41-43] future studies should investigate the relationships between education, other specific cognitive functions, and physical activity. Third, our study was based on correlational data. Accordingly, we cannot exclude reverse causality and thus cannot infer a true causal relationship from education to physical activity through cognitive function.

The study includes at least five strengths. First, it was based on a large sample of non-institutionalized older adults 50 years of age or older from 28 countries. Second, we relied on two statistical approaches suited to formally test mediation processes that provided consistent and complementary results. Third, this is the first study to directly test and support the hypothesized mediating role of cognitive function on the association between educational attainment and physical activity. Fourth, the results of the sensitivity and robustness analyses were consistent with the results of the main analyses. Finally, the robustness analysis with a time lag between the predictors and the outcome minimized the risk of reverse causation bias.

Conclusion

Our findings reveal that cognitive function explains the positive association between educational attainment and physical activity levels. These results not only underline the essential role of education in promoting an active lifestyle, but also uncover the role of cognitive function as an explanatory mechanism for this association. Therefore, health policies and interventions can benefit from special attention to individuals with lower levels of education and could target cognitive function as a leveraging mechanism when aiming to promote a sustained engagement in physical activity.

Author contributions: B.C.: conceptualization, writing – original draft; I.S.: writing – review & editing; S.M.: writing – review & editing; L.F: writing – review & editing; A.F: writing – review & editing; S.S.: data curation, writing – review & editing; S.C.: writing – review & editing; M.P.B.: supervision, writing – review & editing.

Ethical approval: This study was part of the SHARE study, approved by the relevant research ethics committees in the participating countries.

Informed consent: All participants provided written informed consent.

Funding: B.C. is supported by an Ambizione grant (PZ00P1_180040) from the Swiss National Science Foundation (SNSF). M.P.B. is supported by the Natural Sciences and Engineering Research Council of Canada (RGPIN-2021-03153) and by a grant from The Banting Research Foundation.

Data sharing: This SHARE dataset is available at http://www.share-project.org/data-access.html

Acknowledgements: This article uses data from SHARE Wave 1, 2, 4, 5, 6, 7, and 8 (DOIs: 10.6103/SHARE.w1.600, 10.6103/SHARE.w2.600, 10.6103/SHARE.w4.600, 10.6103/SHARE.w5.600, 10.6103/SHARE.w6.600, 10.6103/SHARE.w7.711, 10.6103/SHARE.w8cabeta.001). The SHARE data collection was primarily funded by the European Commission through FP5 (QLK6-CT-2001-00360), FP6 (SHARE-I3: RII-CT-2006-062193, COMPARE: CIT5-CT-2005-028857) and FP7 (SHARE-PREP: no.211909, SHARE-LEAP: no.227822, SHARE M4: no.261982). Additional funding from the German Ministry of Education and Research, the Max Planck Society for the Advancement of Science, the U.S. National Institute on Aging (U01_AG09740-13S2, P01_AG005842, P01_AG08291, P30_AG12815, R21_AG025169, Y1-AG-4553-01, IAG_BSR06-11, OGHA_04-064, HHSN271201300071C), and from various national funding sources is gratefully acknowledged (see www.share-project.org).

REFERENCES

1 Silles, M. A. The causal effect of education on health: Evidence from the United Kingdom. *Econ Educ Rev* **28**, 122-128 (2009).

2 Eide, E. R. & Showalter, M. H. Estimating the relation between health and education: What do we know and what do we need to know? *Econ Educ Rev* **30**, 778-791 (2011).

3 Zajacova, A. & Lawrence, E. M. The relationship between education and health: reducing disparities through a contextual approach. *Annu Rev Public Health* **39**, 273-289 (2018).

4 Conti, G., Heckman, J. & Urzua, S. The education-health gradient. *Am Econ Rev* **100**, 234-238 (2010).

5 Kari, J. T. *et al.* Education leads to a more physically active lifestyle: Evidence based on Mendelian randomization. *Scand J Med Sci Spor* **30**, 1194-1204 (2020).

6 Droomers, M., Schrijvers, C. T. M. & Mackenbach, J. Educational level and decreases in leisure time physical activity: predictors from the longitudinal GLOBE study. *J Epidemiol Community Health* **55**, 562-568 (2001).

7 Chalabaev, A. *et al.* Early-life socioeconomic circumstances and physical activity in older age: Women pay the price. *Psychol Sci* **33**, 212-223 (2022).

8 Cheval, B. *et al.* Effect of early-and adult-life socioeconomic circumstances on physical inactivity. *Med Sci Sports Exerc* **50**, 476-485 (2018).

9 O’Donoghue, G. *et al.* Socio-economic determinants of physical activity across the life course: A" DEterminants of DIet and Physical ACtivity"(DEDIPAC) umbrella literature review. *Plos One* **13**, e0190737 (2018).

10 Beenackers, M. A. *et al.* Socioeconomic inequalities in occupational, leisure-time, and transport related physical activity among European adults: a systematic review. *Int J Behav Nutr Phys Act* **9**, 1-23 (2012).

11 Van Der Heide, I. *et al.* The relationship between health, education, and health literacy: results from the Dutch Adult Literacy and Life Skills Survey. *J Health Commun* **18**, 172-184 (2013).

12 Levin-Zamir, D., Baron-Epel, O. B., Cohen, V. & Elhayany, A. The association of health literacy with health behavior, socioeconomic indicators, and self-assessed health from a national adult survey in Israel. *J Health Commun* **21**, 61-68 (2016).

13 Sun, X. *et al.* Determinants of health literacy and health behavior regarding infectious respiratory diseases: a pathway model. *BMC Public Health* **13**, 1-8 (2013).

14 Friis, K., Lasgaard, M., Rowlands, G., Osborne, R. H. & Maindal, H. T. Health literacy mediates the relationship between educational attainment and health behavior: a Danish population-based study. *J Health Commun* **21**, 54-60 (2016).

15 Stormacq, C., Van den Broucke, S. & Wosinski, J. Does health literacy mediate the relationship between socioeconomic status and health disparities? Integrative review. *Health Promot* **34**, e1-e17 (2019).

16 Verhoeven, L. & Snow, C. E. *Literacy and motivation: Reading engagement in individuals and groups*. (Routledge, 2001).

17 Torres, R. Y. & Marks, R. Relationships among health literacy, knowledge about hormone therapy, self-efficacy, and decision-making among postmenopausal health. *J Health Commun* **14**, 43-55 (2009).

18 Osborn, C. Y., Paasche-Orlow, M. K., Bailey, S. C. & Wolf, M. S. The mechanisms linking health literacy to behavior and health status. *Am J Health Behav* **35**, 118-128 (2011).

19 Nettle, D. Why are there social gradients in preventative health behavior? A perspective from behavioral ecology. *Plos One* **5**, e13371 (2010).

20 Diez Roux, A. V. & Mair, C. Neighborhoods and health. *Ann N Y Acad Sci* **1186**, 125-145 (2010).
21 Cheval, B. *et al.* Cognitive resources moderate the adverse impact of poor neighborhood conditions on physical activity. *Prev Med* **126**, 105741 (2019).
22 Xiao, Q., Keadle, S. K., Berrigan, D. & Matthews, C. E. A prospective investigation of neighborhood socioeconomic deprivation and physical activity and sedentary behavior in older adults. *Prev Med* **111**, 14-20 (2018).
23 Rees-Punia, E., Hathaway, E. D. & Gay, J. L. Crime, perceived safety, and physical activity: A meta-analysis. *Prev Med* **111**, 307-313 (2018).
24 Anstey, K. & Christensen, H. Education, activity, health, blood pressure and apolipoprotein E as predictors of cognitive change in old age: a review. *Gerontology* **46**, 163-177 (2000).
25 Lenehan, M. E., Summers, M. J., Saunders, N. L., Summers, J. J. & Vickers, J. C. Relationship between education and age-related cognitive decline: A review of recent research. *Psychogeriatrics* **15**, 154-162 (2015).
26 Schneeweis, N., Skirbekk, V. & Winter-Ebmer, R. Does education improve cognitive performance four decades after school completion? *Demography* **51**, 619-643 (2014).
27 Avila, R. *et al.* Influence of education and depressive symptoms on cognitive function in the elderly. *Int Psychogeriatr* **21**, 560-567 (2009).
28 Aartsen, M. J. *et al.* Advantaged socioeconomic conditions in childhood are associated with higher cognitive functioning but stronger cognitive decline in older age. *PNAS* **116**, 5478-5486 (2019).
29 Opdebeeck, C., Martyr, A. & Clare, L. Cognitive reserve and cognitive function in healthy older people: a meta-analysis. *Aging Neuropsychol Cogn* **23**, 40-60 (2016).
30 Cheval, B. *et al.* Cognitive functions and physical activity in aging when energy is lacking. *Eur J Ageing* (2022).
31 Cheval, B. *et al.* Relationship between decline in cognitive resources and physical activity. *Health Psychol* **39**, 519-528 (2020).
32 Sabia, S. *et al.* Physical activity, cognitive decline, and risk of dementia: 28 year follow-up of Whitehall II cohort study. *Brit Med J* **357**, j2709 (2017).
33 Cheval, B. *et al.* Association between physical-activity trajectories and cognitive decline in adults 50 years of age or older. *Epidemiol Psychiatr Sci* **30**, e79 (2021).
34 Daly, M., McMinn, D. & Allan, J. L. A bidirectional relationship between physical activity and executive function in older adults. *Front Hum Neurosci* **8**, 1044 (2015).
35 Cheval, B. & Boisgontier, M. P. The theory of effort minimization in physical activity. *Exerc Sport Sci Rev* **49**, 168-178 (2021).
36 Cheval, B. *et al.* Behavioral and neural evidence of the rewarding value of exercise behaviors: a systematic review. *Sports Med* **48**, 1389-1404 (2018).
37 Cheval, B., Sarrazin, P., Boisgontier, M. P. & Radel, R. Temptations toward behaviors minimizing energetic costs (BMEC) automatically activate physical activity goals in successful exercisers. *Psychol Sport Exerc* **30**, 110-117 (2017).
38 Lieberman, D. E. Is exercise really medicine? An evolutionary perspective. *Curr Sports Med Rep* **14**, 313-319 (2015).
39 Klein-Flügge, M. C., Kennerley, S. W., Friston, K. & Bestmann, S. Neural signatures of value comparison in human cingulate cortex during decisions requiring an effort-reward trade-off. *J Neurosci* **36**, 10002-10015 (2016).
40 Prévost, C., Pessiglione, M., Météreau, E., Cléry-Melin, M.-L. & Dreher, J.-C. Separate valuation subsystems for delay and effort decision costs. *J Neurosci* **30**, 14080-14090 (2010).

41 Cheval, B. *et al.* Inhibitory control elicited by physical activity and inactivity stimuli: an EEG study. *Motiv Sci* **7**, 386-389 (2021).

42 Cheval, B. *et al.* Higher inhibitory control is required to escape the innate attraction to effort minimization. *Psychol Sport Exerc* **51**, 101781 (2020).

43 Cheval, B. *et al.* Avoiding sedentary behaviors requires more cortical resources than avoiding physical activity: an EEG study. *Neuropsychologia* **119**, 68-80 (2018).

44 Börsch-Supan, A. *et al.* Data resource profile: the Survey of Health, Ageing and Retirement in Europe (SHARE). *Int J Epidemiol* **42**, 992-1001 (2013).

45 de Souto Barreto, P., Cesari, M., Andrieu, S., Vellas, B. & Rolland, Y. Physical activity and incident chronic diseases: a longitudinal observational study in 16 European countries. *Am J Prev Med* **52**, 373-378 (2017).

46 Boisgontier, M. P. *et al.* Adverse childhood experiences, depressive symptoms, functional dependence, and physical activity: a moderated mediation model. *J Phys Act Health* **17**, 790-799 (2020).

47 United Nations Educational. International Standard Classification of Education 1997. UNESCO, Paris (2006).

48 Cullati, S., Kliegel, M. & Widmer, E. Development of reserves over the life course and onset of vulnerability in later life. *Nat Hum Behav* **2**, 551-558 (2018).

49 Zhao, Q., Lv, Y., Zhou, Y., Hong, Z. & Guo, Q. Short-term delayed recall of auditory verbal learning test is equivalent to long-term delayed recall for identifying amnestic mild cognitive impairment. *Plos One* **7**, e51157 (2012).

50 Sano, M. *et al.* Adding delayed recall to the Alzheimer Disease Assessment Scale is useful in studies of mild cognitive impairment but not Alzheimer disease. *Alzheimer Dis Assoc Disord* **25**, 122-127 (2011).

51 Harris, S. & Dowson, J. Recall of a 10-word list in the assessment of dementia in the elderly. *Br J Psychiatry* **141**, 524-527 (1982).

52 Rosen, W. G. Verbal fluency in aging and dementia. *J Clin Exp Neuropsychol* **2**, 135-146 (1980).

53 Hernán, M. A., Hernández-Díaz, S. & Robins, J. M. A structural approach to selection bias. *Epidemiology* **15**, 615-625 (2004).

54 Digitale, J. C., Martin, J. N. & Glymour, M. M. Tutorial on directed acyclic graphs. *J Clin Epidemiol* **142**, 264-267 (2021).

55 Boisgontier, M. P. & Cheval, B. The anova to mixed model transition. *Neurosci Biobehav Rev* **68**, 1004-1005 (2016).

56 Fritz, M., Taylor, A. & MacKinnon, D. Multivariate behavioral research. *Multivariate Behav Res* **47**, 61-87 (2012).

57 Cheval, B. *et al.* Better subjective sleep quality partly explains the association between self-reported physical activity and better cognitive function. *J Alzheimers Dis* (In press).

58 Tofighi, D. & MacKinnon, D. P. RMediation: An R package for mediation analysis confidence intervals. *Behav Res Methods* **43**, 692-700 (2011).

59 Yzerbyt, V., Muller, D., Batailler, C. & Judd, C. M. New recommendations for testing indirect effects in mediational models: The need to report and test component paths. *J Pers Soc Psychol* **115**, 929-943 (2018).

60 Biesanz, J. C., Falk, C. F. & Savalei, V. Assessing mediational models: Testing and interval estimation for indirect effects. *Multivariate Behav Res* **45**, 661-701 (2010).

61 MacKinnon, D. P., Lockwood, C. M., Hoffman, J. M., West, S. G. & Sheets, V. A comparison of methods to test mediation and other intervening variable effects. *Psychol Methods* **7**, 83-104 (2002).

62 Barton, K. MuMIn: Multi-model inference. R package version 1.42.1. https://CRAN.R-project.org/package=MuMIn (2018).

63 Cheval, B. *et al.* Why are individuals with diabetes less active? The mediating role of physical, emotional, and cognitive factors. *Ann Behav Med* **55**, 904-917 (2021).
64 Stern, Y. What is cognitive reserve? Theory and research application of the reserve concept. *J Int Neuropsychol Soc* **8**, 448-460 (2002).
65 Stern, Y. Cognitive reserve. *Neuropsychologia* **47**, 2015-2028 (2009).
66 Cheval, B. *et al.* Higher inhibitory control is required to escape the innate attraction to effort minimization. *Psychol Sport Exerc* **51**, 101781 (2020).
67 Prince, S. A. *et al.* A comparison of direct versus self-report measures for assessing physical activity in adults: a systematic review. *Int J Behav Nutr Phys Act* **5**, 56 (2008).
68 Fawns-Ritchie, C. & Deary, I. J. Reliability and validity of the UK Biobank cognitive tests. *Plos One* **15**, e0231627 (2020).
69 Davies, G. *et al.* Study of 300,486 individuals identifies 148 independent genetic loci influencing general cognitive function. *Nat Commun* **9**, 1-16 (2018).

Supplemental material

Sensitivity analyses

Table S1. Results excluding participants who dropped out during the survey.
Table S2. Results excluding participants who died during the survey.

Robustness analysis

Table S3. Results of the models including a time lag between the predictors and the outcomes.

Table S1. Results excluding participants who dropped out during the survey.

A. Results of the distribution-of-the-product coefficients approach

(N = 66,434)	**b (95% CI)**
Mediators	
Delayed recall	0.039 (0.033;0.045)
Verbal fluency	0.178 (0.168;0.188)
Proportion of mediated effect	80.6%

Note. 95% CI = confidence interval at 95%. An indirect effect is assumed when the 95% confidence interval around the indirect effect does not include zero.

B. Results of the component approach

(N =66,434)	**Model 1 Cognitive function**				**Model 2 Physical activity**	
Predictors:	**Delayed recall**		**Verbal fluency**			
	b (CI)	***p***	**b (95% CI)**	***p***	**[b] OR (95% CI)**	***p***
Education (ref. Low)	0.49 (0.47;0.51)	<.001	3.44 (3.33;3.55)	<.001	[.05] 1.06 (1.01;1.10)	.013
Cognitive function						
Delayed recall	-	-	-	-	[.08] 1.08 (1.07;1.10)	<.001
Verbal fluency	-	-	-	-	[.05] 1.05 (1.05;1.06)	<.001

Notes. CI = confidence interval at 95%; OR = Odds Ratio. Results are derived from mixed effects models. Models were adjusted for wave of measurement (fixed and random), age, sex, birth cohort, and country of residence

Table S2. Results excluding participants who died during the survey.

A. Results of the distribution-of-the-product coefficients approach

(N = 87,649)	**b (95% CI)**
Mediators	
Delayed recall	0.032 (0.026;0.038)
Verbal fluency	0.16 (0.147;0.165)
Proportion of mediated effect	All

Note. 95% CI = confidence interval at 95%. An indirect effect is assumed when the 95% confidence interval around the indirect effect does not include zero.

B. Results of the component approach

(N = 87,649)	**Model 1 Cognitive function**				**Model 2 Physical activity**	
Predictors:	**Delayed recall**		**Verbal fluency**			
	b (CI)	***p***	**b (95% CI)**	***p***	**[b] OR (95% CI)**	***p***
Education (ref. Low)	0.47 (0.46;0.49)	<.001	3.39 (3.29;3.48)	<.001	[-.03] 0.97 (0.93;1.01)	.098
Cognitive function						
Delayed recall	-	-	-	-	[.07] 1.07 (1.06;1.05)	<.001
Verbal fluency	-	-	-	-	[.05] 1.05 (1.04;1.08)	<.001

Notes. CI = confidence interval at 95%; OR = Odds Ratio. Results are derived from mixed effects models. Models were adjusted for wave of measurement (fixed and random), age, sex, birth cohort, and country of residence

Table S3. Results of the models with a time lag between the predictors and the outcome.

A. Results of the distribution-of-the-product coefficients approach

(N = 53,079)	**b (95% CI)**
Mediators	
Delayed recall	0.041 (0.033;0.049)
Verbal fluency	0.123 (0.111;0.135)
Proportion of mediated effect	55.8%

Note. 95% CI = confidence interval at 95%. An indirect effect is assumed when the 95% confidence interval around the indirect effect does not include zero.

B. Results of the component approach

(N =53,079)	**Model 1 Cognitive function**				**Model 2 Physical activity**	
Predictors:	**Delayed recall**		**Verbal fluency**			
	b (CI)	***p***	**b (95% CI)**	***p***	**[b] OR (95% CI)**	***p***
Education (ref. Low)	0.47 (0.44;0.49)	<.001	3.47 (3.34;3.59)	<.001	[.13] 1.14 (1.08;1.21)	<.001
Cognitive function						
Delayed recall	-	-	-	-	[.09] 1.09 (1.07;1.11)	<.001
Verbal fluency	-	-	-	-	[.04] 1.04 (1.03;1.05)	<.001

Notes. CI = confidence interval at 95%; OR = Odds Ratio. Results are derived from mixed effects models. Models were adjusted for wave of measurement (fixed and random), age, sex, birth cohort, and country of residence