European Journal of Ageing (2022) 19:533–544
https://doi.org/10.1007/s10433-021-00654-2

ORIGINAL INVESTIGATION

Cognitive functions and physical activity in aging when energy is lacking

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Accepted: 16 September 2021 / Published online: 1 October 2021

Abstract
Declines in subjective energy availability and cognitive functions could explain the decrease in physical activity observed across aging. However, how these factors interact remains unknown. Based on the theory of effort minimization in physical activity (TEMPA), we hypothesized that cognitive functions may help older adults to maintain physical activity even when energy availability is perceived as insufficient. This study used data of 104,590 adults from 21 European countries, from the Survey of Health, Ageing and Retirement in Europe (SHARE), including 7 measurement occasions between 2004 and 2017. Cognitive functions were assessed with verbal fluency and delayed recall, using the verbal fluency test and the 10-word delayed recall test. Physical activity and subjective energy availability were self-reported. Results of linear mixed-effects models revealed that cognitive functions moderated the associations between subjective energy availability and physical activity. Moreover, as adults get older, cognitive functions became critical to engage in physical activity regardless the availability of perceived energy. Sensitivity and robustness analyses were consistent with the main results. These results suggest that cognitive functions may help older adults to maintain regular physical activity even when energy for goal pursuit becomes insufficient, but that the protective role of cognitive functions becomes critical at older age, irrespective of the state of perceived energy.

Keywords Cognitive functions · Perceived energy · Physical activity · Health

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Background and objectives

Despite the recognized health benefits of physical activity (Merghani et al. 2016), the general population remains insufficiently active, leading to a pandemic of physical inactivity (Kohl et al. 2012). Every ten seconds worldwide, one person is estimated to die due to physical inactivity (WHO 2010). Older adults are particularly vulnerable, with physical activity sharply declining over aging (Cheval et al. 2018a; DiPietro 2001; Laddu et al. 2020).

This decline is characterized by a large heterogeneity, which may be explained by various factors, notably physiological and psychosocial ones. We focused on one psychosocial factor that is garnering growing interest in the self-regulation literature: *subjective energy availability*. Defined as one's perceived potential to pursue a goal (Cardini and Freund 2020), this concept is closely related to self-efficacy and effort. For example, people might have the willingness and feel capable (self-efficacy) to walk 30 min five days a week, but at the same time they might feel insufficiently rested to do it on the planned day (subjective energy availability), resulting in choosing not to spend any energy to reach this goal (effort). Subjective energy availability may be especially important in the domain of physical activity, because engaging in regular physical activity is among the most energy-consuming health behaviors (McEachan et al. 2010), not only at the physical but also at the mental level (Forestier et al. 2018).

One problem is that there are several reasons to expect subjective energy availability to decrease as people grow older. Indeed, aging is associated with declines in physical and cognitive functions (Baltes and Smith 2003; Baltes et al. 1998). In addition, coping with negative age stereotypes has been shown to consume mental energy to self-regulate (Emile et al. 2015). These barriers could lead people to perceive themselves as having insufficient energy as they age. A recent study has provided support to this idea, by showing that older adults reported having less energy available for physical activities than younger ones (Cardini and Freund 2020). However, at the time of writing, no study to our knowledge has yet tested whether a decrease in subjective energy availability is associated with a decrease in physical activity in older adults. Moreover, factors that may help older adults engage in physical activity despite the lack of subjective energy are still unclear.

According to the theory of effort minimization in physical activity (TEMPA; Cheval and Boisgontier 2021) people have an automatic attraction to effort minimization, thereby favoring engagement in physically inactive behaviors. For example, in line with TEMPA, multiple studies have shown that this automatic attraction to effort minimization is involved in the regulation of physical activity behavior (Cheval et al. 2015, 2018d, 2020a, 2021; Bernacer et al. 2019). Crucially, TEMPA argues that because people are automatically attracted by effort minimization, cognitive functions, referring to multiple cognitive domains such as memory, language, perception, attention, and executive functions (Lezak et al. 2004), should play a key role in counteracting this attraction. Consistent with this suggestion, experimental and epidemiological studies confirmed that cognitive functions are important for avoiding sedentary temptations (Cheval et al. 2017, 2018d, 2020a, 2021) and for favoring the maintenance of physical activity across aging (Cheval et al. 2019b, 2020b; Sabia et al. 2017; Daly et al. 2015; Snowden et al. 2011; Young et al. 2015; Lindwall et al. 2012). For example, based on a computerized task, Cheval et al. (2018a, b, c, d) showed that participants exhibited greater brain activity associated with conflict monitoring and inhibitory control when virtually avoiding stimuli depicting sedentary behaviors. Likewise, Cheval et al. (2020a, b) showed that better cognitive functioning, as indexed by performance on the verbal fluency and delayed recall tests, was associated with higher level and less steep decreases in physical activity across aging. These findings confirm that cognitive function may be critical to counteract the automatic attraction to effort minimization, thereby promoting engagement in physical activity. However, whether cognitive functions can reduce the negative association between the lack of subjective energy availability and physical activity in older adults remains unknown.

The goal of the present research was to assess the association between subjective energy availability and physical activity and to investigate whether cognitive functions can moderate this relationship. Based on the aforementioned literature (Cardini and Freund 2020), we hypothesized that the lack of subjective energy availability would be negatively associated with physical activity (H1). Moreover, based on the TEMPA (Cheval and Boisgontier 2021; Cheval et al. 2018b), we hypothesized that greater cognitive function would reduce the negative association between the lack of subjective energy availability and physical activity (H2).

Research design and methods

Study population and design

Our analyses used data from the Survey of Health, Ageing and Retirement in Europe—SHARE—a European study (21 countries) of individuals aged 50 or older including 7 repeated measurements between 2004 and 2017. SHARE was described in detail elsewhere (Börsch-Supan et al. 2013). In short, participants were sampled based on probability selection methods. Individuals eligible for the study were people aged 50 years or older and their partner, irrespective of age (although we did not analyze data from participants younger than 50). Data was collected using computer-assisted personal interviewing (CAPI) in participants' homes. The study was initiated in 2004 and followed by six subsequent waves with approximately two-year intervals and wave 7 being completed in 2017. Wave 3 was devoted to data collection related to childhood histories (SHARELIFE). This wave did not contain any data related to physical activity, subjective energy availability and cognitive functions and was therefore not used in the current study. Specifically, physical activity, subjective energy availability and cognitive functions (delayed recall and verbal fluency) were assessed at measurements 1, 2, 4, 5, 6 and 7. A final sample size of 104,590 participants aged 50–96 years with at least one measure of physical activity, subjective energy availability and cognitive functions were included in our models. The relevant local research ethics committees in the participating countries approved SHARE. All participants provided written informed consent.

Measures

Physical activity

Physical activity was measured using two items (Lindwall et al. 2011; de Souto Barreto et al. 2017; Cheval et al. 2018c). Moderate physical activity was assessed using this item: "How often do you engage in activities that require a low or moderate level of energy such as gardening, cleaning the car, or doing a walk?" Vigorous physical activity was assessed using this item: "How often do you engage in activities that require a vigorous level of energy such as sports, heavy housework, or a job that involves physical labour?" For each item, participants answered on a 4-point scale: 0 = hardly ever, or never; 1 = one to three times a month; 2 = once a week; 3 = more than once a week. An overall score of physical activity ranging from 0 to 6 was created by summing up the scores of the two questions, with higher scores reflecting greater physical activity.

Subjective energy availability

Subjective energy availability for goal pursuit was assessed using the following item: "In the last month, did you have too little energy to do things you wanted to do?" Participants answered Yes or No. Although using a dichotomous scale may seem to reduce the sensitivity of measurement, we believe instead that such measure is particularly relevant. Indeed, we were not interested in assessing the perceived amount of energy, but focused instead on whether people perceive they have or do not have sufficient energy for goal pursuit. As such, using a binary scale better taps into the construct of interest than a quantitative scale.

Cognitive functions

In the 10-word delayed recall test (Harris and Dowson 1982), participants listened to a list of ten words that were read out loud by the interviewer. Immediately after reading the wordlist, participants were asked to recall as many words as possible. This was asked again after a delay during which the verbal fluency took place. Verbal fluency is thought to reflect executive functioning, which includes executive control or selective inhibition (Lezak et al. 2004), for instance. The delayed recall score is the number of words that the respondent is able to recall, which ranges from 0 to 10. In the verbal fluency test (Rosen 1980), participants named as many different animals as they could think of in 60 s. The score we used consisted of the total number of correctly named animals. Delayed recall is believed to reflect an indicator of early-cognitive impairment (Zhao et al. 2012). Verbal fluency and delayed recall are thought to represent two indicators of fluid cognitive function, which has often been found to decline with aging (Aartsen et al. 2019). Of note, a delayed memory recall measure (rather than an immediate recall measure) was used because it has previously been shown to be particularly sensitive to early detection of mild cognitive impairment (Sano et al. 2011). This choice is consistent with previous literature investigating cognitive function in aging (Aartsen et al. 2019; Aichele et al. 2018; Cheval et al. 2019b, 2020b).

Covariates

The covariates and confounders included in the statistical models were sex (male, female), education (primary, secondary, tertiary), household's ability to make ends meet (easily, fairly easily, with difficulty, with great difficulty), birth cohort [war (between 1914 and 1918 and between 1939 and 1945), Great Depression (between 1929 and 1938), no war and no economic crisis (before 1913, between 1919 and 1928, and after 1945)], chronic conditions (e.g., hypertension, diabetes), body mass index, dementia (dementia/no dementia), and country of residence (Austria, Belgium, Croatia, Czech Republic, Denmark, Estonia, France, Germany, Greece, Hungary, Ireland, Israel, Italy, Luxembourg, Netherlands, Poland, Portugal, Slovenia, Spain, Sweden, Switzerland). Participants' attrition [no dropout, dropout (participants who did not respond to both wave 5 and 6), death] was also controlled for.

Statistical analysis

Data were analyzed using mixed-effects models to account for the nested structure of the data (i.e., repeated observations within a single participant) (Boisgontier and Cheval 2016). Moreover, mixed-effects models do not require an equal number of observations from all participants. Therefore, participants with missing observations were included in these models. Specifically, physical activity trajectories over aging were estimated in an accelerated longitudinal design (Duncan et al. 1996). The models included linear and quadratic terms for age, and the a priori covariates and cofounders as fixed effects. The quadratic term for age was added to assess accelerated (or decelerated) changes of physical activity across aging. Age was centered at the midpoint of the sample's age range (73 years) and was then divided by 10 (this allows a simpler interpretation of the parameters and reduced risk of model convergence issues). The coefficients yielded effects of the physical activity rate of change over a 10-year period. The models included random intercepts and random (linear and quadratic) slopes. These random effects estimated each participant's engagement in physical activity and the rate of change of this engagement over time. For time-varying covariates, we used the mode to reduce observation loss.

Model 1 included interaction terms between subjective energy availability and cognitive functions to test whether cognitive functions moderated the association between perceived energy and engagement in physical activity. Interaction terms (i.e., three-way interactions) between subjective energy availability, cognitive functions, and age (linear and quadratic) were included in Model 2 to test whether cognitive functions moderated the influence of subjective energy availability on the trajectory of physical activity across aging. A statistically significant interaction would indicate that the associations of subjective energy availability with the level of physical activity (i.e., Model 1) and its evolution across aging (i.e., Model 2) depend on cognitive functions. The models were fitted with one indicator of cognitive functions at a time, but we also fitted a fully adjusted model that included the two indicators of cognitive functions. Statistical analyses were performed using the lme4 and lmerTest packages in R (Bates et al. 2015; R Core Team, 2017; Kuznetsova et al. 2016). The pseudo R^2 were calculated as an estimate of the effect size.

Five sensitivity analyses were performed: (1) including additional covariates likely to influence both cognitive functions and physical activity: partner status (i.e., living with a partner vs. living alone), smoking behavior (pack-year smoking), depressive symptoms, and self-rated health, (2) excluding participants with dementia, (3) excluding participants who died during the survey, (4) excluding participants who dropped out during the survey, and (5) excluding participants with fewer than 3 measures. Finally, a robustness analysis was conducted, in which we introduced a time lag between the time-varying predictors (i.e., subjective energy availability and cognitive functions) and the outcome (i.e., physical activity)—i.e., for a given wave (except for baseline), the time-varying predictors were assigned the value of the preceding wave. This robustness analysis aimed to minimize the impact of reverse causation bias. Supplemental material 1 provides more details on all covariates used in the sensitivity analyses.

Results

After descriptive statistics, main results are reported in two sections. The first section describes the results of the analyses testing the associations between subjective energy availability and physical activity. The second section describes the results of the analyses testing the moderating role of cognitive functions on these associations.

Participants' characteristics

Table 1 reports participants' characteristics as a function of their baseline subjective energy availability. The final sample included 104,590 participants (244,692 observations) living in 21 European countries. Participants completed on average 2.3 measures of physical activity over the six waves and the number of participants with only one measurement wave was 35,120 (33.6%).

Participants who reported insufficient energy reported less frequent engagement in moderate and vigorous physical activity, showed worse delayed recall and verbal fluency, had lower education, and were more likely to be older, male, to have fewer than 2 chronic conditions and to drop out or die during the survey than participants who reported sufficient energy for goal pursuit at baseline. Subjective energy availability showed an accelerated decline with aging (p value for linear and quadratic effect of age < 0.001).

Subjective energy availability and physical activity

Table 1 presents the summary of the models assessing the associations between perceived energy and physical activity level and its trajectory across aging, as well as the moderating effect of cognitive functions on these associations (note that covariates are not represented in this table, see Table S1 for full information).

In Model 1, consistent with our first hypothesis, results showed that subjective energy availability was negatively associated with physical activity ($b = -0.40$, [95%CI] $= -0.41$ to -0.38 $p < 0.001$). Moreover, in Model

Table 1 Sample characteristics by perceived energy level at baseline

	Insufficient perceived energy ($N = 36{,}133$)		Sufficient perceived energy ($N = 68{,}764$)		p value
Physical activity	3.3	2.1	4.2	1.8	< 0.001
Cognitive resources					
Delayed recall (number of words), SD	3.9	2.1	3.9	2.1	< 0.001
Verbal Fluency (number of words), SD	18.5	7.5	20.3	7.6	< 0.001
Covariates					
Age at baseline (years), SD	65.0	10.4	62.9	9.3	< 0.001
Gender					
Women	22,389	62.0%	34,986	51.1%	
Men	13,744	38.0%	33,471	48.8%	< 0.001
Education					
Primary	10,055	27.8%	14,438	21.1%	
Secondary	19,770	54.7%	38,220	55.8%	
Tertiary	6308	17.5%	15,799	23.1%	< 0.001
Household's ability to make ends meet					
Easily	10,129	28.0%	27,364	40.0%	
Fairly easily	10,416	28.8%	20,551	30.0%	
With some difficulty	9281	25.7%	13,886	20.3%	
With great difficulty	6307	17.5%	6656	9.7%	< 0.001
Chronic conditions					
More than two	15,583	43.1%	44,544	65.1%	
Less than two	20,550	56.9%	23,913	34.9%	< 0.001
Body mass index (kg/m^2), SD	27.3	4.8	26.7	4.2	
Dementia					
No	34,188	94.6%	66,749	97.5%	
Yes	1945	5.4%	1708	2.5%	< 0.001
Countries					
Belgium	2901	8.0%	5454	8.0%	
Austria	1420	3.9%	4181	6.1%	
Denmark	1608	4.4%	3552	5.2%	
France	2545	7.0%	4410	6.4%	
Germany	2163	6.0%	4907	7.2%	
Greece	1664	4.6%	4148	6.0%	
Israel	978	2.7%	1956	2.9%	
Italy	2495	6.9%	4821	7.0%	
Netherlands	1442	4.0%	3740	5.5%	
Spain	2922	8.1%	4492	6.6%	
Sweden	1863	5.2%	3783	5.5%	
Switzerland	1124	3.1%	2949	4.3%	
Czech Republic	2522	7.0%	5464	8.0%	
Ireland	284	0.8%	655	1.0%	
Poland	1263	35%	1574	2.3%	
Estonia	3818	10.6%	3442	5.0%	
Hungary	1426	3.9%	1424	2.1%	
Portugal	621	1.7%	1316	1.9%	
Slovenia	1485	4.1%	3526	5.2%	
Luxembourg	633	1.8%	1290	1.9%	
Croatia	956	2.6%	1373	2.0%	< 0.001
Birth cohort					
After 1945	18,373	50.8%	39,730	58.0%	
Between 1939 and 1945	6663	18.4%	13,689	20.0%	

Table 1 (continued)

	Insufficient perceived energy (N = 36,133)		Sufficient perceived energy (N = 68,764)		p value
Between 1929 and 1938	7862	21.8%	11,537	16.9%	
Between 1919 and 1928	3235	9.0%	3501	5.1%	< 0.001
Attrition					
No drop out	23,022	63.7%	45,179	66.0%	
Drop out	8749	24.2%	18,652	27.2%	
Death	4362	12.1%	4626	6.8%	< 0.001

p-values are based on the analyses of variance and chi-square tests for continuous and categorical variables, respectively, testing the association between subjective energy availability (sufficient vs. insufficient) and these variables. *SD* standard deviation

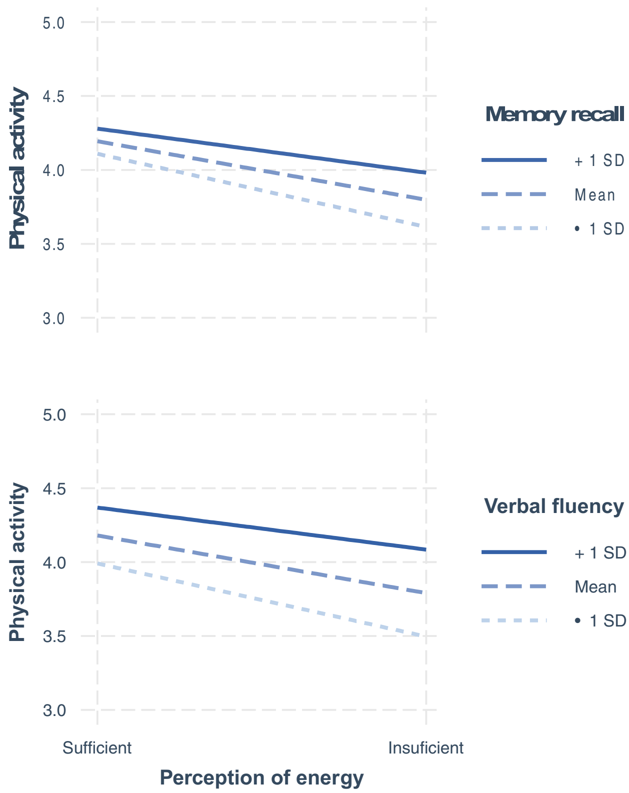

Fig. 1 The moderating role of cognitive functions on the associations between the levels of subjective energy availability and physical activity. SD = standard deviation

2 testing the trajectories of physical activity across aging, results showed that a lack of subjective energy availability was associated with a steeper linear decline in physical activity across aging ($b = -0.07$, [95%CI] = -0.09 to -0.05 $p < 0.001$).

Moderating role of cognitive functions

In Model 1, delayed recall and verbal fluency moderated the association between subjective energy availability and physical activity ($b = 0.10$, [95%CI] = 0.08–0.11 $p < 0.001$ for delayed recall; $b = 0.11$, [95%CI] = 0.09–0.12 $p < 0.001$ for verbal fluency)—the negative association between perceived energy and physical activity was more pronounced in participants with lower levels of verbal fluency and delayed recall (Fig. 1). Simple effects tests further revealed that cognitive functions were positively associated with physical activity when participants reported sufficient energy ($b = 0.09$, [95%CI] = 0.08–0.10 $p < 0.001$ for delayed recall; $b = 0.19$, [95%CI] = 0.18–0.20 $p < 0.001$ for verbal fluency), but the effects were even more pronounced when participants reported having insufficient energy for goal pursuit ($b = 0.18$, [95%CI] = 0.17–0.20 $p < 0.001$ for delayed recall; $b = 0.30$, [95%CI] = 0.28–0.31 $p < 0.001$ for verbal fluency). In the fully adjusted model, the cognitive indicators still moderated the association between perceived energy and the level of physical activity ($p < 0.001$). In other words, consistent with our second hypothesis, results revealed that cognitive functions reduced the negative association between the lack of subjective energy availability and physical activity.

In Model 2 testing trajectories of physical activity across aging, results showed that lower levels of delayed recall and verbal fluency were associated with a steeper decline in physical activity across aging ($p < 0.001$ for both linear and quadratic effect of age for both cognitive indicators). Crucially, the two cognitive indicators moderated the association between subjective energy availability and the linear and quadratic effect of age ($p < 0.001$). The positive effects of cognitive functions on physical activity increased as adults aged when participants reported sufficient energy for goal pursuit. In other words, at older age, cognitive functions become critical to predict physical activity, irrespective of the state of perceived energy (Fig. 2). The associations remained unchanged in the fully adjusted model including the two cognitive functions.

This last model explained 35.1% of the variance in physical activity, of which 4.3% was explained by perceived energy and 1.6% by cognitive functions. Additionally, the model explained 22.3% of the differences in the linear trajectories of physical activity over time, of which

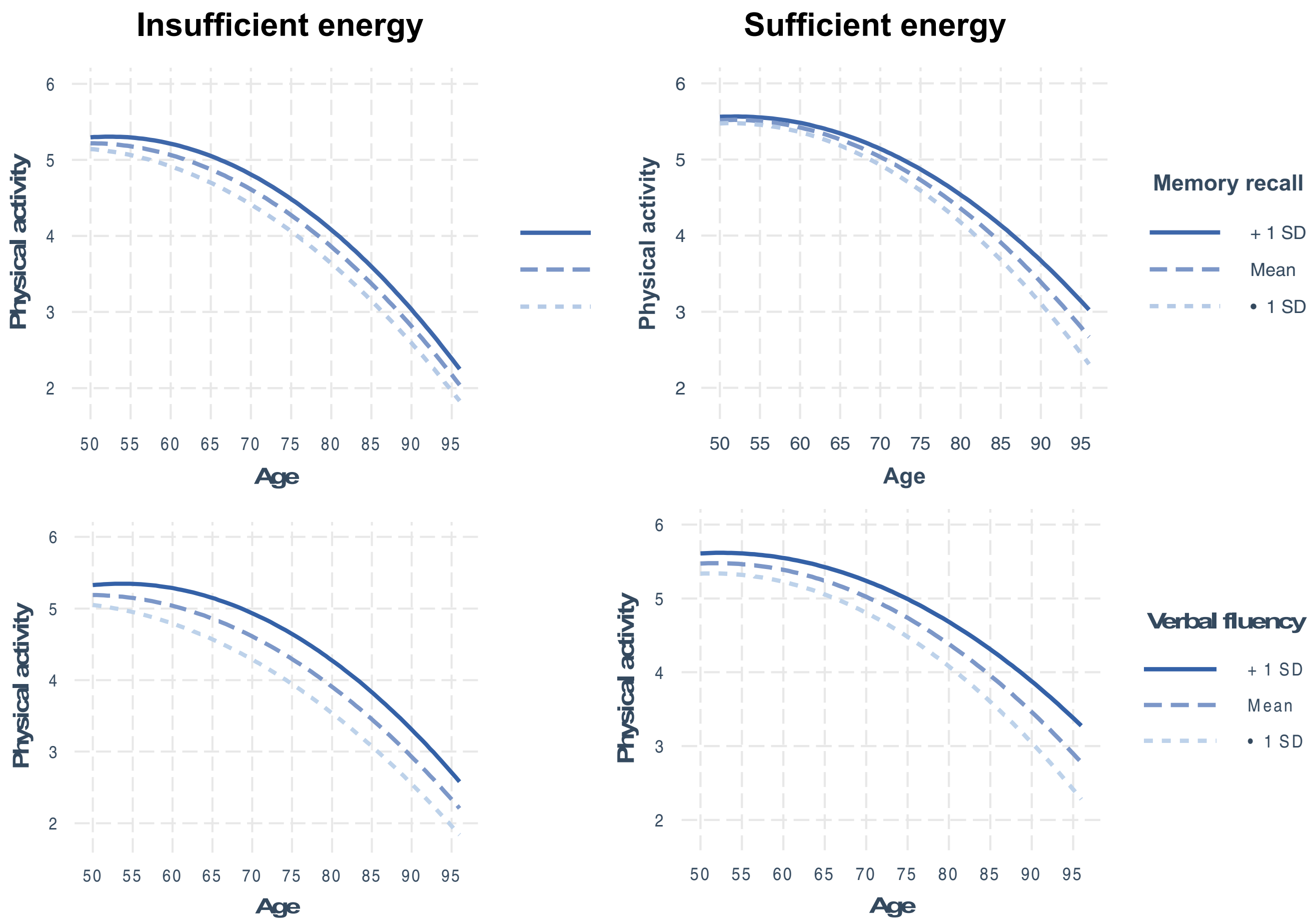

Fig. 2 The moderating role of cognitive functions and subjective energy availability on the changes of physical activity across aging. SD = standard deviation

2.1% was explained by perceived energy and 2.4% by cognitive functions. Finally, the model explained 20.7% of the differences in the quadratic trajectories of physical activity over time, of which 5.8% was explained by perceived energy and 3.1% by cognitive functions (Table 2).

Sensitivity and robustness analyses

The sensitivity and robustness analyses (Table S2) yielded results that were similar to those of the main analyses. Specifically, based on both the p-values and the effect estimates, results showed that cognitive functions moderated the association between subjective energy availability and physical activity across the five sensitivity analyses. Results of the robustness analysis testing the cross-lagged associations showed that subjective energy availability was prospectively associated with physical activity, and that cognitive functions moderated this association.

Discussion and implications

This study examined whether cognitive functions may help older adults maintain physical activities even when they perceive their energy availability to be insufficient. Results of this large-scale longitudinal study ($N = 104{,}590$) showed that the lack of subjective energy availability was associated with lower levels of physical activity and a steeper decline across aging. We further observed that these associations were moderated by cognitive functions—the negative relationship between the lack of subjective energy availability and physical activity engagement was significantly reduced in people with higher compared to lower cognitive functions. Finally, the protective role of cognitive functions became higher at older age, irrespective of the state of perceived energy. Hence, our study suggests that cognitive functions may help older adults to engage in physical activity even when the lack of subjective energy favors engagement in physically inactive behaviors. These

Table 2 Associations of subjective energy availability and cognitive functions with the levels and trajectories of physical activity across aging

Level	Model delayed recall only				Model verbal fluency only				Model with the two cognitive indicators			
	b (95% CI)	*p*-value	*b* (95% CI)	*p*-value	*b* (95% CI)	*p*-value	*b* (95% CI)	*p*-value	*b* (95% CI)	*p*-value	*b* (95% CI)	*p*-value
Intercept	4.81 (4.74–4.89)	< 0.001	4.86 (4.78–4.93)	< 0.001	4.81 (4.74–4.89)	< 0.001	4.86 (4.78–4.93)	< 0.001	4.82 (4.75–4.89)	< 0.001	4.87 (4.79–4.94)	< 0.001
Subjective energy availability (ref. sufficient)												
Insufficient	− 0.40 (− 0.41 to 0.38)	< 0.001	− 0.45 (− 0.47 to 0.43)	< 0.001	− 0.39 (− 0.41 to 0.38)	< 0.001	− 0.43 (− 0.45 to 0.41)	< 0.001	− 0.39 (− 0.40 to 0.37)	< 0.001	− 0.43 (− 0.45 to 0.40)	< 0.001
Cognitive resources												
Delayed recall	0.09 (0.08–0.10)	< 0.001	0.13 (0.11–0.14)	< 0.001					0.05 (0.04–0.06)	0.001	0.08 (0.07–0.10)	< 0.001
Verbal fluency					0.09 (0.08–0.09)	< 0.001	0.12 (0.11–0.12)	< 0.001	0.09 (0.08–0.09)	< 0.001	0.11 (0.10–0.12)	< 0.001
Subjective energy availability × Delayed recall	0.10 (0.08–0.11)	< 0.001	0.08 (0.06–0.10)	< 0.001					0.06 (0.05–0.08)	< 0.001	0.04 (0.02–0.07)	< 0.001
Subjective energy availability × Verbal fluency					0.11 (0.09–0.12)	< 0.001	0.10 (0.08–0.12)	< 0.001	0.07 (0.06–0.09)	< 0.001	0.08 (0.06–0.10)	< 0.001
Rate of change (trajectories)												
Age (10-years follow-up)	− 0.68 (− 0.70 to 0.66)	< 0.001	− 0.62 (− 0.65 to 0.60)	< 0.001	− 0.65 (− 0.67 to 0.62)	< 0.001	− 0.59 (− 0.61 to 0.56)	< 0.001	− 0.63 (− 0.65 to 0.61)	< 0.001	− 0.57 (− 0.60 to 0.54)	< 0.001
Age (10 years) squared	− 0.16 (− 0.17 to 0.15)	< 0.001	− 0.15 (− 0.16 to 0.13)	< 0.001	− 0.16 (− 0.17 to 0.15)	< 0.001	− 0.14 (− 0.15 to 0.13)	< 0.001	− 0.15 (− 0.16 to 0.15)	< 0.001	− 0.13 (− 0.14 to 0.12)	< 0.001
Subjective energy availability (ref. no)												
Linear effect												
Yes			− 0.07 (− 0.09 to 0.05)	< 0.001			− 0.06 (− 0.08 to 0.04)	< 0.001			− 0.06 (− 0.09 to 0.04)	< 0.001
Quadratic effect												
Yes			0.00 (− 0.02 to 0.01)	0.714			0.00 (− 0.01 to 0.02)	0.857			0.00 (− 0.02 to 0.01)	0.714
Cognitive resources												
Linear effect												
Delayed recall			0.07 (0.05–0.08)	< 0.001							0.04 (0.03–0.06)	< 0.001
Verbal fluency							0.08 (0.06–0.09)	< 0.001			0.06 (0.04–0.08)	< 0.001

Table 2 (continued)

Level	Model delayed recall only				Model verbal fluency only				Model with the two cognitive indicators			
	b (95% CI)	*p*-value	*b* (95% CI)	*p*-value	*b* (95% CI)	*p*-value	*b* (95% CI)	*p*-value	*b* (95% CI)	*p*-value	*b* (95% CI)	*p*-value
Subjective energy availability × Delayed recall	− 0.04 (− 0.06 to 0.02)	< 0.001									− 0.04 (− 0.06 to 0.02)	0.060
Subjective energy availability × Verbal fluency							− 0.03 (− 0.05 to 0.01)	0.008			− 0.01 (− 0.03 to 0.01)	0.408
Quadratic effect												
Delayed recall			0.01 (0.00–0.02)	0.003							0.01 (− 0.00 to 0.02)	0.297
Verbal fluency							0.02 (0.01–0.02)	0.001			0.01 (0.00–0.02)	0.041
Subjective energy availability × Delayed recall			− 0.03 (− 0.04 to 0.01)	< 0.001							− 0.02 (− 0.03 to 0.00)	0.027
Subjective energy availability × Verbal fluency							− 0.03 (− 0.04 to 0.02)	< 0.001			− 0.02 (− 0.04 to 0.00)	0.012

All models included a random intercept and linear slopes for age. Age (10 y follow-up) represents the evolution of physical activity over a 10-year period. Covariates are not included in this table (see Table S1 for full information). Model 1(left column of each model) included interaction terms between subjective energy availability and cognitive functions. Interaction terms (i.e., three-way interactions) between subjective energy availability, cognitive functions, and age (linear and quadratic) were included in Model 2 (right column of each model) findings are consistent with TEMPA (Cheval and Boisgontier 2021).

Our finding showing that a lack of subjective energy is negatively associated with physical activity is in line with previous literature (Cardini and Freund 2020) and extends it by revealing that this effect can be observed not only on the level but also on the evolution of physical activity across aging. This negative association was hypothesized and can be explained by the fact that engaging in physically active behaviors requires a high level of energy compared with other health-related behaviors (McEachan et al. 2010). The age-related decline in physical fitness (Cheval et al. 2018a, 2019a; Caspersen et al. 1985; Hesseberg et al. 2016) can make daily-life physical activities more challenging, even those involving low level of energy expenditure. This process may explain why the influence of subjective energy availability on physical activity was found to be particularly strong in older age.

Our finding that cognitive functions moderated the adverse effect of insufficient subjective energy availability on both the level and trajectories of physical activity across aging is consistent with previous studies observing that the protective role of cognitive functions may be especially pronounced when environmental factors (i.e., neighborhood conditions) favor engagement in physically inactive behaviors (Cheval et al. 2019b). Our results confirmed that this protective role of cognitive functions also applies to individual-related factors (i.e., subjective energy availability). Finally, as observed for subjective energy, the moderating role of cognitive functions is particularly pronounced as adults get older. This result is consistent with the hypothesis that subjective energy availability is particularly relevant when internal factors such as aging increase the perceived effort required in a given behavior (Cardini and Freund, 2020).

A critical contribution of the study is to provide a better understanding of the protective role of cognitive functions, which helped older adults to maintain physical activity participation even when availability of energy was perceived as insufficient. A potential explanation of the beneficial role of cognitive functions lies in TEMPA (Cheval et al. 2018b; Cheval and Boisgontier 2021), which argues that cognitive functions are essential to favor engagement in physical activity, an influence that is hypothesized to be particularly pronounced when situational factors, such as the ones related to the individual (e.g., fatigue or low subjective energy availability) or the environmental (e.g., neighborhood conditions) levels, drive individuals toward physically inactivity. However, it should be noted that, although consistent with TEMPA, this result provides only indirect evidence as other mechanisms not related to the ability to counteract the ones of effort minimization can account for the associations observed. For example, the higher level of physical activity can reflect a more efficient implementation of their intention into action.

Strengths and limitations

Among the strengths of the present study are the large sample size (104,590 participants living in 21 European countries), the repeated measurement of physical activity covering a large range of ages (50–96 years), the repeated assessment of cognitive functions allowing to study not only the level but also the change in physical activity across aging, and the measurements of two indicators of cognitive functions. Moreover, the results were consistent across five sensitivity analyses and one robustness analysis. These methodological strengths allowed to test the theoretical assumptions of TEMPA in a large-scale prospective study, thereby improving our understanding of the role of subjective energy availability and cognitive functions in physical activity engagement across aging.

However, at least three limitations should be noted. First, our study was based on correlational data and as such, reverse causation between physical activity and perceived energy availability, as suggested by previous studies (Puetz et al. 2006), cannot be excluded. Although our robustness analysis investigating the cross-lagged associations minimized this bias. Second, our results are based on self-reported measures of physical activity, which may lead to results that substantially differ from those that would have been obtained using a device-based measure (e.g., accelerometers) (Prince et al. 2008; Skender et al. 2016). Likewise, this measure lacks granularity (i.e., assessed only four frequency levels) and does not cover all the types of physical activities in which older individuals can engage during their daily life (i.e., mostly primed individuals' response toward activities related to house chores and recreational activities). Future studies using such device-based measures of physical activity are thus needed. Third, subjective energy availability was measured with a binary variable (yes/no), which may reduce the sensitivity to evaluate this construct. However, we believe that such measure may be particularly relevant because it directly taps into the concept of interest. Indeed, it assesses whether people perceive whether they have or not sufficient energy for goal pursuit, and as such, allows to disentangle this perception from the perceived amount of energy. Likewise, subjective energy availability was assessed only every two years. As such, this variable is possibly more associated with a general and stable state of energy perception than daily and short-term fluctuations of perceived energy. Using a daily assessment approach, as recommended by Dunton (2018) could be particularly meaningful to examine short-term fluctuations in perceived energy and their impact on physical activity implementation (Rebar et al. 2018).

Conclusion and clinical implications

In conclusion, our findings provide support for the critical role of cognitive functions to favor engagement in physical activity, especially when individuals perceived having too little energy for goal pursuit and get older. Policies for healthy aging and intervention to promote physical activity may be more effective if they target both cognitive functions and subjective energy availability. Future interventional studies are needed to investigate the effectiveness of such multi-component interventions.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10433-021-00654-2.

Authors' contributions B.C. and A.C. designed the analyses. B.C. analyzed the data. B.C., M.P.B. and A.C. drafted the manuscript. All authors critically appraised and approved the final version of the manuscript.

Funding This work was supported by an Ambizione grant (PZ00P1_180040) from the Swiss National Science Foundation (SNSF) provided to the first author of the manuscript. 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. 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, SHARELIFE: CIT4-CT-2006-028812) 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 http://www.share-project.org).

Availability of data and material This paper uses data from SHARE Waves 1, 2, 3 (SHARELIFE), 4, 5 and 6 (DOIs: https://doi.org/10.6103/SHARE.w1.600, https://doi.org/10.6103/SHARE.w2.600, https://doi.org/10.6103/SHARE.w3.600, https://doi.org/10.6103/SHARE.w4.600, https://doi.org/10.6103/SHARE.w5.600, https://doi.org/10.6103/SHARE.w6.600).

Code availability R code will be available upon request from the first author.

Declarations

Conflicts of interest The authors declare that they have no conflict of interest.

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