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Research Article

Cognitive Reserve Moderates Associations Between Walking Performance Under Single- and Dual-Task Conditions and Incident Mobility Impairment in Older Adults

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Abstract

Background: Among older adults, walking performance is a reliable indicator of adverse health outcomes including incident mobility impairment. Whereas, attention and executive functions have been implicated in cognitive control of locomotion, much less is known about the role of cognitive reserve (CR) in predicting mobility impairments among older adults. Specifically, whether CR moderates the relationship between gait performance and incident mobility impairment has not been reported. To address this gap in the literature, we examined whether gait performance under single-task walk (STW) and dual-task walk (DTW) conditions predicted incident mobility impairment and whether CR moderated this relationship.

Method: Participants were 176 (mean age = 75.57; % female = 53) older adults with baseline Short Physical Performance Battery (SPPB) scores of 10–12. Participants completed neuropsychological testing, the SPPB, and a DTW protocol. CR was evaluated using the Wide Range Achievement Test, third edition. Participants were followed for 3 years; individuals whose SPPB scores declined below 10 were defined as incident cases of mobility impairment ($n = 42$).

Results: Moderation analyses revealed significant interaction effects of CR with walking velocity under STW ($b = 0.09$, 95% CI [0.01, 0.17], $z = 2.30$, $p = .02$) and DTW ($b = 0.10$, 95% CI [0.02, 0.17], $z = 2.55$, $p = .01$) conditions, wherein slower gait predicted increased risk of incident mobility impairment among individuals with lower CR.

Conclusion: These findings extend knowledge about the interrelation of cognitive and mobility functions, revealing the critical role of CR in identifying older adults at risk of developing incident mobility impairment.

Keywords: Gait, Physical function, Risk factors, Successful aging

Slower walking during single-task walk (STW) conditions is associated with more difficulties completing activities of daily living (1) and increased risk of cardiovascular disease, disability, and mortality (2,3). Slower walking under attention-demanding dual-task walk (DTW) conditions is predictive of incident frailty, disability, and mortality even after adjustment for STW performance (4). The longitudinal associations of DTW performance with adverse outcomes, among older adults, further suggest that cognitive motor performance, when combined, may confer predictive utility for incident mobility dysfunction that is independent of gait performance assessed under STW conditions.

Research has indeed provided unequivocal evidence that locomotion and cognition are interrelated (for reviews, see refs. (5–7)). Studies examining the relationship between cognitive functions and walking under STW and DTW conditions in older adults have often focused on attention and executive functions (8–10). Better executive functions and faster speed of processing have also been associated with better performance on more comprehensive measures of physical functioning, such as the Short Physical Performance Battery (SPPB) (11–13).

Cognitive reserve (CR) refers to individual differences in the ability to adapt and optimize task performance vis-a-vis brain aging, pathology, or insult. Research has shown that CR is protective against incident cognitive decline and dementia. Specifically, individuals with higher CR are better able to cope with neurodegenerative processes and therefore demonstrate a lesser degree of objective cognitive decline when compared to those with similar brain pathology but lower CR (14,15). It is hypothesized that CR can be improved by enriching life experiences, educational advancement, and occupational attainment (among others). Such enrichment enhances and strengthens functional brain networks thereby allowing them to optimize performance and processing efficiency (15). Proxies of CR are variable including sociodemographic variables and objective cognitive tests of reading and verbal IQ. While objective performance measures operationalizing CR are less sensitive and thus more resistant to the deleterious effect of aging, as compared to cognitive measures of executive functions and memory, CR can be enhanced through various leisure activities (16) making it an attractive candidate for interventions. Few studies, however, have considered the relationship between CR and mobility outcomes. For instance, Holtzer et al. (17) found that latent factors measuring speed/executive attention and verbal IQ were both significant predictors of recurrent falls. General cognition (18,19) as well as CR and memory (20) were also used to predict gait speed decline. Importantly, no study to date has examined the role of CR in predicting longitudinal decline on more comprehensive measures of physical functioning, such as the SPPB.

The present study was designed to address these gaps in the literature. Specifically, we aimed to determine whether gait velocity during STW and DTW conditions predicted incident mobility impairment among relatively healthy community-residing older adults, and whether this relationship was moderated by CR. Longitudinal decline in SPPB scores was used to operationalize incident mobility impairment. We hypothesized that slower gait velocity during STW and DTW conditions would be associated with greater odds of developing mobility impairment at a 3-year follow-up period. We further hypothesized that CR, defined using the Wide Range Achievement Test, third edition (WRAT-3), would moderate this relationship, wherein poor walking performance would be predictive of incident mobility impairment among older adults with low CR.

Method

Participants

Participants were 176 older adults (65+ years), enrolled in the Central Control of Mobility and Aging (10) study, who met eligibility criteria for the current study and had complete baseline and annual assessments data conducted over a 3-year follow-up period. General exclusion criteria were: inability to speak or understand English, visual or auditory impairment, inability to walk independently, recent hospitalization for a condition that affects mobility, residence in a nursing home, and diagnosis of a serious illness, psychiatric condition, or neurodegenerative disease. Using a structured telephone interview that assessed medical and psychological history, mobility, and functional abilities (21), prospective participants were also screened for dementia using a validated instrument (22). Individuals who passed the initial telephone interview were invited to annual, in-person visits in which trained research assistants administered comprehensive neuropsychological, psychological, and mobility assessments. Dementia diagnoses were assigned at consensus diagnostic case conferences (23). In order to be included in the current study, participants were required to have SPPB scores of 10 or higher at baseline and complete annual SPPB evaluations during the 3-year follow-up (see the "Incident mobility impairment" section for further details). The work described in this manuscript has been executed in adherence with The Code of Ethics of the World Medical Association (Declaration of Helsinki) and the APA ethical standards set for research involving human participants. The study was approved by the Albert Einstein College of Medicine Institutional Review Board, and written informed consent was obtained from all participants in the first in-person study visit.

Measures and Procedures

Walking protocol

As detailed in previous research (10), the walking paradigm included a STW, a single-task alpha (STA; cognitive interference task), and a DTW condition. The participants walked for 1 trial, which consisted of 3 consecutive loops (40 feet per loop including 6 straight walks and 5 turns), under the single- and dual-task conditions. In the STW condition, the participants were instructed to walk at his or her normal pace along the walkway. The STA condition required participants to recite alternate letters of the alphabet, beginning with "A," while standing still for 30 seconds. In the DTW condition, the participants were instructed to walk while reciting alternate letters of the alphabet beginning with "B." Outcome measures for the current study included walking performance (gait velocity) and correct letter generation. The reliability and validity of the walking paradigm have been well established by previous research (20).

Quantitative gait assessment

Zenometrics system.—A 4- × 20-foot Zeno electric walkway using ProtoKinetics Movement Analysis Software (PKMAS) was used to assess various quantitative measures of gait. The current investigation utilized the measure of gait velocity (Zenometrics, LLC, Peekskill, NY) as described in previous publications (24).

Short Physical Performance Battery

The SPPB includes tests of balance, gait speed, and chair rise. Each portion is scored on a scale of 0–4, with a possible total score ranging from 0 to 12, with higher scores indicating better performance (25). The SPPB was administered and scored according to the standardized protocol (26). The SPPB takes approximately 5 minutes to complete and is a well-validated measure of physical ability (25).

Covariates

Disease burden, as measured by the Global Health Status (GHS) score, was calculated based on reported presence or absence of 10 health conditions including diabetes, chronic heart failure, arthritis, hypertension, depression, stroke, Parkinson's disease, chronic obstructive lung disease, angina, and myocardial infarction (23). Other covariates included age, sex, and the rate of correct letter generation under the DTW and STA conditions.

Incident mobility impairment

Incident mobility impairment was defined objectively and operationalized by measuring changes in SPPB performance during the 3-year follow-up. Individuals with baseline SPPB scores of 10–12 (indicating no physical impairment) were included in the analyses. Individuals whose SPPB scores fell below 10 during the 3-year follow-up were categorized as incident cases of mobility impairment. Individuals who maintained SPPB scores in the range of 10–12 were categorized as having no mobility impairment.

Cognitive reserve

The WRAT-3 (27) was used to measure CR. The WRAT-3 word reading performance, a widely used measure of CR, has established construct validity (28) and, in assessment of older adults, is relatively stable over time (29,30). The WRAT-3 reading score is calculated by summing the number of words that a participant is able to correctly read/pronounce, from a list of irregularly spelled words. Because inspection of the WRAT-3 scores suggested the data were not normally distributed (Shapiro–Wilk test of normality, $W(176) = 0.92$, $p < .01$), and to facilitate the interpretation of the moderation analyses, WRAT-3 scores were dichotomized using a median split to create 2 groups: (i) high and (ii) low CR.

Statistical Analyses

Descriptive statistics (mean ± *SD*) were provided for each of the continuous variables for the entire cohort and also stratified by mobility impairment status. The Hayes PROCESS macro (25) was utilized to examine the moderating effect of CR on the relationship between STW and DTW velocity and incident mobility impairment. For dichotomous outcomes such as incident mobility impairment, the Hayes macro uses logistic regression models to estimate the 2-way interactions that operationalize moderation effects. Specifically, the model uses ordinary least squares regression and computes interaction terms of *X* (predictor variable) and *W* (moderator variable) to identify whether the strength or direction of relationship between predictor and outcome variables is influenced by a moderator variable. Herein, separate regression models with STW and DTW velocity as the predictor variables, incident mobility impairment (developed mobility impairment/ did not develop mobility impairment) as the outcome variable, and CR as the moderator were carried out. An additional regression model examined whether a dual-task cost (DTC) in velocity ([STW velocity − DTW velocity]/STW velocity) predicted incident mobility impairment. Analyses were first run unadjusted. Then, fully adjusted models were conducted controlling for age, sex, global health status, and the rate of correct letter generation under the DTW condition. To address the possible effect of significant life stressors on study outcomes, additional moderation analyses (as described above) were carried out adjusting for incident adverse health events over the follow-up period. These included change in global health status score (indicating the development of a new comorbidity), incident falls, incident hospitalizations, and incident dementia diagnosis. SPSS statistical software package (version 26; SPSS, Inc., Chicago, IL) with the Hayes PROCESS macro was used for statistical analyses. The level of statistical significance was set at $p = .05$.

Results

Participants ($n = 176$; mean age = 75.57 ± 6.17 years; mean education = 14.6 ± 2.91 years; % female = 53%) who completed the full protocol for years 1–4 were included in the study. The original sample included 549 participants, but after excluding those who had dementia ($n = 3$) and SPPB scores <10 ($n = 197$) at baseline, and those who did not complete the SPPB during the 3-year follow-up ($n = 173$), the final sample was comprised of 176 participants. The average WRAT-3 score (109.07 ± 8.98) was indicative of average to high-average estimated premorbid intelligence. The average GHS score (1.43 ± 1.02) was suggestive of good health. Sample characteristics as well as mean values for gait velocity are summarized in Table 1.

Prediction of Incident Mobility Impairment

The first unadjusted moderation analysis revealed a negative association between STW velocity and incident mobility impairment ($b = -0.10$, 95% CI [−0.17, −0.04], $z = -3.09$, $p < .01$). Additionally, there was a significant interaction effect of STW velocity × CR for predicting incident mobility impairment ($b = 0.09$, 95% CI [0.01, 0.16], $z = 2.26$, $p = .02$). Specifically, an analysis of the conditional effects of focal predictors revealed that, among those with low CR, slower STW velocity was associated with greater risk of incident mobility impairment ($b = -0.10$, 95% CI [−0.17, −0.04], $z = -3.09$, $p < .01$). The second unadjusted model revealed a significant negative association between DTW velocity and incident mobility impairment ($b = -0.11$, 95% CI [−0.18, −0.05], $z = -3.40$, $p < .01$). Moreover, there was a significant moderation effect, operationalized via the interaction of DTW velocity × CR, for predicting incident

Table 1. Sample Characteristics

	Total Sample at Baseline $n = 176$	No Mobility Impairment $n = 134$	Incident Mobility Impairment $n = 42$	*T* Statistic	*p* Value
	Mean (*SD*)	Mean (*SD*)	Mean (*SD*)		
Sex (% female)	93 (53%)	75 (56%)	18 (42.9%)		
Age (years)	75.57 (6.17)	74.68 (6.01)	78.44 (5.87)	−3.60	<.01
GHS (total score)	1.43 (1.02)	1.38 (1.04)	1.60 (0.96)	−1.12	.24
Cognitive reserve (max WRAT-3 score)	109.07 (8.98)	109.35 (9.18)	108.19 (8.32)	0.73	.47
Education (years)	14.6 (2.91)	15.13 (2.98)	14.12 (3.58)	1.82	.07
STW velocity (cm/s)	76.29 (13.82)	78.12 (13.86)	70.68 (12.24)	2.99	<.01
DTW velocity (cm/s)	63.44 (15.54)	65.92 (15.14)	55.78 (14.38)	3.68	<.01
DTC	0.17 (0.15)	0.15 (0.15)	0.21 (0.13)	−2.29	.73
STA correct letter generation rate (letter/second)	0.58 (0.20)	0.58 (0.19)	0.58 (0.23)	0.16	.82
DTW correct letter generation rate (letters/second)	0.61 (0.26)	0.61 (0.26)	0.59 (0.28)	0.76	.68
Incident hospitalizations (frequencies)	74	46	28	−3.84	<.01
Incident falls (frequencies)	87	62	25	−1.50	.14
Incident dementia diagnosis (frequencies)	6	3	3	−1.53	.13

Notes: DTC = dual-task cost; DTW = dual-task walking; GHS = Global Health Status score; STA = single-task alpha; STW = single-task walking; WRAT = Wide Range Achievement Test, third edition. Incident hospitalizations, incident falls, and incident dementia diagnoses reflect frequencies.

mobility impairment (b = 0.09, 95% CI [0.02, 0.17], z = 2.52, p = .01). Examination of the conditional effects of focal predictors revealed that, among those with low CR, slower DTW velocity was associated with greater risk of incident mobility impairment (b = −0.11, 95% CI [−0.18, −0.05], z = −3.40, p < .01). The fully adjusted moderation models, summarized in Tables 2 and 3, revealed that the moderation effects of CR on the associations between gait velocity under STW and DTW conditions and incident mobility impairment remained significant. Furthermore, the conditional effects of focal predictors also remained significant in the DTW model demonstrating that, among those with low CR, slower DTW velocity was associated with greater risk of mobility impairment (b = −0.10, 95% CI [−0.16, −0.03], z = −2.74, p < .01). The conditional effect in the STW model was no longer statistically significant (b = −0.07, 95% CI [−0.14, 0.01], z = −1.81, p = .07).

A separate regression analysis revealed that DTC in velocity predicted incident mobility impairment (b = 4.52, 95% CI [0.23, 8.81], z = 2.06, p = .04). However, this relationship was not moderated by CR (see Table 4).

Supplemental analyses that included the covariate for the rate of correct letter generation under the STA condition were not materially different from the fully adjusted analyses shown in Table 2 and 3 that controlled for rate of correct letter generation under DTW condition (see Supplementary Tables 1 and 2).

Sensitivity Analysis: Impact of Adverse Events on Study Outcomes

The analyses summarized in Supplementary Tables 3 and 4 controlled for change in global health status score over the follow-up period. The moderating effect of CR on the relationship between walking velocity and incident mobility impairment remained significant for both STW and DTW conditions (STW: b = 0.09, 95% CI [0.01, 0.17], z = 2.27, p = .02; DTW: b = 0.10, 95% CI [0.02, 0.18], z = 2.55, p = .01). The analyses summarized in Supplementary Tables 5 and 6 controlled for incident falls over the follow-up period. The moderating effect of CR on the relationship between walking velocity and incident mobility impairment remained significant for both STW and DTW conditions (STW: b = 0.09, 95% CI [0.01, 0.17], z = 2.27, p = .02; DTW: b = 0.10, 95% CI [0.02, 0.17], z = 2.53, p = .01). The analyses summarized in Supplementary Tables 7 and 8 controlled for incident hospitalizations over the follow-up period. Incident hospitalization was a significant predictor of incident mobility impairment for both STW and DTW conditions (STW: b = 1.49, 95% CI [0.61, 2.36], z = 3.33, p < .01; DTW: b = 1.59, 95% CI [0.69, 2.48], z = 3.49, p < .01). The moderating effect of CR on the relationship between walking velocity and incident mobility impairment remained significant for both STW and DTW conditions (STW: b = 0.10, 95% CI [0.03, 0.18], z = 2.58, p = .01; DTW: b = 0.12, 95% CI [0.04, 0.20], z = 2.91, p < .01). Finally, the analyses summarized in Supplementary Tables 9 and 10 controlled for incident dementia diagnosis over the follow-up period. The moderating effect of CR on the relationship between walking velocity and incident mobility impairment remained significant for both STW and DTW conditions (STW: b = 0.10, 95% CI [0.02, 0.18], z = 2.36, p = .02; DTW: b = 0.11, 95% CI [0.03, 0.20], z = 2.68, p = .01).

Discussion

We found that CR moderated associations between gait velocity under STW and DTW conditions and incident mobility impairment.

Table 2. Cognitive Reserve Moderates the Association Between STW Velocity and Incident Mobility Impairment

	Coefficient	*SE*	Z	*p*	LLCI	ULCI
Constant	−0.41	3.85	−0.11	.92	−7.96	7.14
STW velocity (cm/s)	−0.07	0.04	−1.81	.07	−0.14	0.01
WRAT-3	−6.66	2.90	−2.30	.02	−12.34	−0.99
STW velocity × WRAT-3	0.09	0.04	2.30	.02	0.01	0.17
Sex	0.49	0.41	1.19	.23	−0.32	1.30
Age (years)	0.07	0.03	1.99	.05	<0.01	0.13
GHS (total score)	0.12	0.21	0.55	.58	−0.30	0.53
DTW velocity (cm/s)	−0.03	0.02	−1.68	.09	−0.07	0.01
DTW correct letter generation rate	−0.07	0.83	−0.09	.93	−1.69	1.55

Notes: DTW = dual-task walk; GHS = Global Health Status score; LLCI = lower limit confidence interval; STW = single-task walk; ULCI = upper limit confidence interval; WRAT-3 = Wide Range Achievement Test, third edition. DTW correct letter generation rate was measured in letters/second.

Table 3. Cognitive Reserve Moderates the Association Between DTW Velocity and Incident Mobility Impairment

	Coefficient	*SE*	Z	*p*	LLCI	ULCI
Constant	−0.47	3.81	−0.12	.90	−7.94	6.99
DTW velocity (cm/s)	−0.10	0.04	−2.74	.01	−0.16	−0.03
WRAT-3	−5.65	2.22	−2.54	.01	−10.01	−1.29
DTW velocity × WRAT-3	0.10	0.04	2.55	.01	0.02	0.17
Sex	0.41	0.42	0.97	.33	−0.41	1.23
Age (years)	0.06	0.03	1.85	.06	< −0.01	0.13
GHS (total score)	0.08	0.21	0.37	.71	−0.34	0.50
STW velocity (cm/s)	−0.01	0.02	−0.44	.66	−0.06	0.04
DTW correct letter generation rate	−0.02	0.85	−0.03	.98	−1.69	1.64

Notes: DTW = dual-task walk; GHS = Global Health Status score; LLCI = lower limit confidence interval; STW = single-task walk; ULCI = upper limit confidence interval; WRAT-3 = Wide Range Achievement Test, third edition. DTW correct letter generation rate was measured in letters/second.

Table 4. DTC Velocity Predicts Incident Mobility Impairment

	Coefficient	*SE*	*Z*	*p*	LLCI	ULCI
Constant	−9.17	2.66	−3.44	<.01	−14.39	−3.95
DTC velocity (cm/s)	4.52	2.19	2.06	.04	0.23	8.81
WRAT-3 (max score)	0.67	0.70	0.96	.34	−0.70	2.03
DTC velocity × WRAT-3	−3.71	2.89	−1.28	.20	−9.37	1.95
Sex	0.45	0.41	1.10	.27	−0.35	1.24
Age (years)	0.08	0.03	2.64	.01	0.02	0.15
GHS (total score)	0.15	0.20	0.76	.45	−0.24	0.55
DTW correct letter generation rate	−0.30	0.80	−0.37	.71	−1.87	1.27

Notes: DTC = dual-task cost; DTW = dual-task walk; GHS = Global Health Status score; LLCI = lower limit confidence interval; ULCI = upper limit confidence interval; WRAT-3 = Wide Range Achievement Test, third edition. DTW letter generation rate was measured in letters/second.

Specifically, unadjusted models revealed that slower STW and DTW velocity predicted incident mobility impairment only among those individuals with low CR. When adjusted for covariates, the moderation effects for both models remained significant. Our findings revealed that both STW and DTW velocity have independent utility in predicting incident mobility impairment, notably when moderated by CR, as both moderation analyses controlled for performance in the other walking condition. However, further adjusted conditional effects of focal predictors demonstrated that, among those with low CR, slower DTW velocity, but not STW velocity, was associated with greater risk of incident mobility impairment at follow-up. Such a pattern of results, reflecting a stronger effect in the DTW model, can be explained by the greater cognitive demands inherent in the DTW condition as compared to the STW condition. Larger DTCs in gait velocity, which are indicative of more limited attentional resources, were predictive of incident mobility impairment, but these results were not moderated by CR. Reasons for the absence of the moderation effect of CR are not clear. It is possible, however, that because DTC may be less stable than the individual measures they consist of, the power to detect the interaction of DTC by CR may have been reduced. Additionally, the moderating effect of CR on the association between DTC and incident mobility impairment may be evinced in studies that include both healthy and disease populations and thereby offer a greater contrast in gait speed changes across conditions.

The present study investigated incident mobility impairment in the context of normal aging. To evaluate the possible effects of significant life stressors on study outcomes, we examined whether the observed effects remained while accounting for adverse health events. We conducted supplementary analyses adjusting for changes in health status, incident falls, incident hospitalizations, and incident dementia over the follow-up period. Importantly, the moderating effect of CR on the associations between gait velocity under the STW and DTW conditions and incident mobility impairment remained even when adjusting for these significant adverse events. The finding that incident hospitalizations was a significant predictor of incident mobility impairment is noteworthy but not surprising as hospitalization has been associated with functional decline (31). The novelty, though, is demonstrated in that the significant moderating effect of CR on the relationship between STW and DTW velocity and incident mobility impairment remained significant even when accounting for incident hospitalizations. This suggests that factors other than those directly related to physical functioning impact incident physical impairment.

Taken together, our findings may suggest that high CR compensates for slower walking ability and is protective against incident mobility impairment over time. This pattern of results illustrates the import of the interrelation of mobility and cognitive functions vis-à-vis predictive models of adverse outcomes in aging. These results are supported by prior research demonstrating that CR is protective against adverse health outcomes in aging (32) and highlight the importance of engaging in activities that promote CR in order to reduce risk of functional decline. Another possible explanation for the present findings is that individuals with high versus low CR experience different disablement processes. It is well established that higher CR is associated with delayed onset of cognitive decline in the context of brain pathology (14,15,33). Similarly, it may be that incident mobility impairment may occur at different time points for individuals with low versus high CR, resulting in different associations between gait speed and incident mobility impairment.

Clinical Implications

Our results support and extend the clinical utility of objective gait assessment as a predictor of adverse health outcomes in community-residing older adults. Furthermore, the moderating role of CR in the relationship between gait velocity and incident mobility impairment highlights the importance of building and maintaining one's reserve capabilities in order to protect against age-related functional decline. Research has shown that CR can increase throughout the life span in response to enriching social, physical, and cognitive activities (16), suggesting that health care providers and those involved in caring for older adults, as well as family members of older adults, should recommend participation in such activities to support healthy aging.

Study Strengths, Limitations, and Future Directions

A key strength of the research was the use of objective assessments for measuring mobility impairment and CR. The SPPB allowed for standardized, objective measurement of mobility functioning. Similarly, quantifying CR by using the WRAT-3, allowed for objective assessment of premorbid abilities. While the WRAT-3 is widely accepted as being correlated with premorbid intellectual ability, the construct of CR is multidimensional and may not be fully captured by a singular measure. Future research may expand upon the measurement of CR and consider whether different measures of reserve produce different outcomes.

Our findings may provide a potential framework for measuring physical resilience longitudinally in the context of normal aging. Physical resilience, which refers to one's ability to resist functional physical decline or return to premorbid physical functioning following a stressor, is often examined in the context of an acute stressor or negative health event (34). However, physical resilience can also be examined in the context of more gradual stressors, such as aging, by observing longitudinal functional trajectories. While Whitson et al. (34) express that there is still debate regarding whether normal aging can be considered a stressor for examining physical resilience, our results may provide support for examining the construct of physical resilience longitudinally in the context of normal aging. Specifically, a key concern around the consideration of normal aging as a stressor is how to conceptually and empirically account for adverse life events and acute stressors that occur over time and might influence physical resilience. Our supplementary analyses revealed that CR moderated the relationship between STW and DTW velocity and incident mobility impairment while controlling for 4 key health stressors, (development of a new comorbidity, incident falls, incident hospitalizations, and incident dementia). In controlling for such adverse health events, the present study design may represent a useful framework for identifying modifiable predictors of physical resilience in the context of normal aging as a gradual stressor.

Prior research (20) reported that the protective effect of executive functions against decline in gait speed was stronger among those with higher CR. The present study extends the role of CR in cognitive control of locomotion to broader definitions of mobility impairments. Furthermore, much of the prior research on the relationship between mobility and cognition has focused on cognitive functions known to decline with age. Broadening the scope of this area of research, the present study adds to the limited, but growing body of literature examining the important role of CR in predicting mobility outcomes among older adults.

The present research was not without its limitations, however. While gait velocity has been shown to be predictive of adverse health outcomes, this measure represents only one facet of quantitative walking performance. Research has demonstrated the utility of other gait characteristics, such as double support time and gait variability, in predicting adverse outcomes in older adults (35). It is possible that other measures of gait performance will offer incremental utility in predicting incident mobility impairment. Hence, future research should consider examining whether longitudinal associations between other quantitative measures of gait and incident mobility impairment are moderated by CR.

Given the present study utilized a sample of relatively healthy older adults, the results may not be generalizable to those with significant medical conditions or physical limitations. The sample size was limited due to availability of follow-up data, as not all participants who enrolled in the study completed the SPPB during the 3-year follow-up. In order to assess the generalizability of the current results, future research studies with larger older adult cohorts should be conducted to replicate the findings reported herein. The present study utilized an SPPB cut score of 10, with scores below 10 indicating incident mobility impairment. While prior research has demonstrated that scores below 10 are associated with increased risk of mobility disability (36), scores just below 10 represent relatively mild levels of impairment. Hence, it is possible that we have categorized older adults with relatively mild mobility limitations as incident cases of mobility impairment. Research examining the utility of the SPPB in predicting disability found that those with SPPB scores between 7 and 9 had significantly higher risk of developing mobility disability (relative risk 1.5–2.1) compared to those with SPPB scores between 10 and 12 (24). Additionally, in a sample of previously hospitalized individuals, SPPB scores less than or equal to 7 were associated with significantly higher risk of rehospitalization (25). Given this, future research may consider using a different, more stringent SPPB cut score of 7 to specifically target more severe levels of loss of function as proxies for incident mobility impairment. It is also worth noting that gait velocity in the present study was slow due to the fact that participants were instructed to walk in loops. It is well established that entering and exiting turns reduce gait speed (24,37). However, the effects of dual-task interference on the decline in gait velocity from STW to DTW observed herein and in previous studies that utilized a straight walk design (9,10) were comparable. Moreover, gait velocities, assessed in PKMAS under the current protocol requiring the participants to walk in loops and separately in GAITRite, which employed a straight walk design, were highly correlated (38). Hence, the walking velocities reported in the current study are ecologically valid and generalizable. Finally, our analyses controlled for a large number of possible confounders providing confidence in the reported moderating effects of CR on the associations between gait velocity and incident mobility impairment.

Conclusion

In summary, we found that gait velocity predicted incident mobility impairment among older adults with low CR even when adjusting for adverse life stressors. This suggests that higher CR is protective against incident mobility impairment possibly by compensating for slower walking ability. Taken together, these findings highlight the import of the interrelation between mobility and cognitive functions, notably vis-à-vis predictive models of adverse health outcomes in aging. Furthermore, the present study provides a possible framework for measuring physical resilience objectively using longitudinal study designs.

Supplementary Material

Supplementary data are available at *The Journals of Gerontology, Series A: Biological Sciences and Medical Sciences* online.

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Conflict of Interest

None declared.

References

1. Verghese J, Wang C, Holtzer R. Relationship of clinic-based gait speed measurement to limitations in community-based activities in older adults. *Arch Phys Med Rehabil.* 2011;92(5):844–846. doi:10.1016/j.apmr.2010.12.030
2. Newman AB, Simonsick EM, Naydeck BL, et al. Association of long-distance corridor walk performance with mortality, cardiovascular disease, mobility limitation, and disability. *J Am Med Assoc.* 2006;295(17):2018–2026. doi:10.1001/jama.295.17.2018
3. Studenski S, Perera S, Patel K, et al. Gait speed and survival in older adults. *J Am Med Assoc.* 2011;305(1):50–58. doi:10.1001/jama.2010.1923
4. Verghese J, Holtzer R, Lipton RB, Wang C. Mobility stress test approach to predicting frailty, disability, and mortality in high-functioning older adults. *J Am Geriatr Soc.* 2012;60(10):1901–1905. doi:10.1111/j.1532-5415.2012.04145.x
5. Clouston SA, Brewster P, Kuh D, et al. The dynamic relationship between physical function and cognition in longitudinal aging cohorts. *Epidemiol Rev.* 2013;35(1):33–50. doi:10.1093/epirev/mxs004
6. Li KZH, Bherer L, Mirelman A, Maidan I, Hausdorff JM. Cognitive involvement in balance, gait and dual-tasking in aging: a focused review

from a neuroscience of aging perspective. *Front Neurol.* 2018;9:913. doi:10.3389/fneur.2018.00913
7. Paraskevoudi N, Balcı F, Vatakis A. "Walking" through the sensory, cognitive, and temporal degradations of healthy aging. *Ann NY Acad Sci.* 2018;1426(1):72–92. doi:10.1111/nyas.13734
8. Holtzer R, Verghese J, Xue X, Lipton RB. Cognitive processes related to gait velocity: results from the Einstein Aging Study. *Neuropsychology.* 2006;20(2):215–223. doi:10.1037/0894-4105.20.2.215
9. Holtzer R, Wang C, Verghese J. The relationship between attention and gait in aging: facts and fallacies. *Motor Control.* 2012;16(1):64–80. doi:10.1123/mcj.16.1.64
10. Holtzer R, Wang C, Verghese J. Performance variance on walking while talking tasks: theory, findings, and clinical implications. *Age (Dordr).* 2014;36(1):373–381. doi:10.1007/s11357-013-9570-7
11. Bruce-Keller AJ, Brouillette RM, Tudor-Locke C, et al. Relationship between cognitive domains, physical performance, and gait in elderly and demented subjects. *J Alzheimers Dis.* 2012;30(4):899–908. doi:10.3233/JAD-2012-120025
12. Schneider BC, Lichtenberg PA. Physical performance is associated with executive functioning in older African American women. *J Aging Res.* 2011;2011:578609. doi:10.4061/2011/578609
13. Vazzana R, Bandinelli S, Lauretani F, et al. Trail Making Test predicts physical impairment and mortality in older persons. *J Am Geriatr Soc.* 2010;58(4):719–723. doi:10.1111/j.1532-5415.2010.02780.x
14. Stern Y. What is cognitive reserve? Theory and research application of the reserve concept. *J Int Neuropsychol Soc.* 2002;8(3):448–460.
15. Stern Y. Cognitive reserve in ageing and Alzheimer's disease. *Lancet Neurol.* 2012;11(11):1006–1012. doi:10.1016/S1474-4422(12)70191-6
16. Najar J, Östling S, Gudmundsson P, et al. Cognitive and physical activity and dementia: a 44-year longitudinal population study of women. *Neurology.* 2019;92(12):e1322–e1330. doi:10.1212/WNL.0000000000007021
17. Holtzer R, Friedman R, Lipton RB, Katz M, Xue X, Verghese J. The relationship between specific cognitive functions and falls in aging. *Neuropsychology.* 2007;21(5):540–548. doi:10.1037/0894-4105.21.5.540
18. Atkinson HH, Rapp SR, Williamson JD, et al. The relationship between cognitive function and physical performance in older women: results from the Women's Health Initiative Memory Study. *J Gerontol A Biol Sci Med Sci.* 2010;65(3):300–306. doi:10.1093/gerona/glp149
19. Atkinson HH, Rosano C, Simonsick EM, et al.; Health ABC Study. Cognitive function, gait speed decline, and comorbidities: the Health, Aging and Body Composition Study. *J Gerontol A Biol Sci Med Sci.* 2007;62(8):844–850. doi:10.1093/gerona/62.8.844
20. Holtzer R, Wang C, Lipton R, Verghese J. The protective effects of executive functions and episodic memory on gait speed decline in aging defined in the context of cognitive reserve. *J Am Geriatr Soc.* 2012;60(11):2093–2098. doi:10.1111/j.1532-5415.2012.04193.x
21. Baker PS, Bodner EV, Allman RM. Measuring life-space mobility in community-dwelling older adults. *J Am Geriatr Soc.* 2003;51(11):1610–1614. doi:10.1046/j.1532-5415.2003.51512.x
22. Galvin JE, Roe CM, Powlishta KK, et al. The AD8: a brief informant interview to detect dementia. *Neurology.* 2005;65(4):559–564. doi:10.1212/01.wnl.0000172958.95282.2a
23. Holtzer R, Verghese J, Wang C, Hall CB, Lipton RB. Within-person across-neuropsychological test variability and incident dementia. *J Am Med Assoc.* 2008;300(7):823–830. doi:10.1001/jama.300.7.823
24. Holtzer R, Mahoney JR, Izzetoglu M, Wang C, England S, Verghese J. Online fronto-cortical control of simple and attention-demanding locomotion in humans. *Neuroimage.* 2015;112:152–159. doi:10.1016/j.neuroimage.2015.03.002
25. Guralnik JM, Simonsick EM, Ferrucci L, et al. A Short Physical Performance Battery assessing lower extremity function: association with self-reported disability and prediction of mortality and nursing home admission. *J Gerontol.* 1994;49(2):M85–M94. doi:10.1093/geronj/49.2.m85
26. Treacy D, Hassett L. The Short Physical Performance Battery. *J Physiother.* 2018;64(1):61. doi:10.1016/j.jphys.2017.04.002
27. Wilkinson GS. *Wide Range Achievement Test: WRAT3. Revised 3, 1993 Edition.* Wilmington, DE: Wide Range, Inc.; Los Angeles, CA: Western Psychological Services [distributor]; 1993.
28. Sayegh P, Arentoft A, Thaler NS, Dean AC, Thames AD. Quality of education predicts performance on the Wide Range Achievement Test—4th Edition Word Reading Subtest. *Arch Clin Neuropsychol.* 2014;29(8):731–736. doi:10.1093/arclin/acu059
29. Ashendorf L, Jefferson AL, Green RC, Stern RA. Test–retest stability on the WRAT-3 reading subtest in geriatric cognitive evaluations. *J Clin Exp Neuropsychol.* 2009;31(5):605–610. doi:10.1080/13803390802375557
30. Andrew FH. *Introduction to Mediation, Moderation, and Conditional Process Analysis: A Regression-Based Approach (Methodology in the Social Sciences).* 2nd ed. The Guilford Press; 2018.
31. Zisberg A, Shadmi E, Gur-Yaish N, Tonkikh O, Sinoff G. Hospital-associated functional decline: the role of hospitalization processes beyond individual risk factors. *J Am Geriatr Soc.* 2015;63(1):55–62. doi:10.1111/jgs.13193
32. Scarmeas N, Stern Y. Cognitive reserve and lifestyle. *J Clin Exp Neuropsychol.* 2003;25(5):625–633. doi:10.1076/jcen.25.5.625.14576
33. Stern Y. Cognitive reserve. *Neuropsychologia.* 2009;47(10):2015–2028. doi:10.1016/j.neuropsychologia.2009.03.004
34. Whitson HE, Duan-Porter W, Schmader KE, Morey MC, Cohen HJ, Colon-Emeric CS. Physical resilience in older adults: systematic review and development of an emerging construct. *J Gerontol A Biol Sci Med Sci.* 2016;71(4):489–495. doi:10.1093/gerona/glv202
35. Jayakody O, Breslin M, Srikanth VK, Callisaya ML. Gait characteristics and cognitive decline: a longitudinal population-based study. *J Alzheimers Dis.* 2019;71(suppl. 1):S5–S14. doi:10.3233/JAD-181157
36. Vasunilashorn S, Coppin AK, Patel KV, et al. Use of the Short Physical Performance Battery score to predict loss of ability to walk 400 meters: analysis from the InCHIANTI Study. *J Gerontol A Biol Sci Med Sci.* 2009;64(2):223–229. doi:10.1093/gerona/gln022
37. England SE, Verghese J, Mahoney JR, Trantzas C, Holtzer R. Three-level rating of turns while walking. *Gait Posture.* 2015;41(1):300–303. doi:10.1016/j.gaitpost.2014.09.010
38. Holtzer R, Verghese J, Allali G, Izzetoglu M, Wang C, Mahoney JR. Neurological gait abnormalities moderate the functional brain signature of the posture first hypothesis. *Brain Topogr.* 2016;29(2):334–343. doi:10.1007/s10548-015-0465-z