Intra-individual lap time variation of the 400-m walk, an early mobility indicator of executive function decline in high-functioning older adults?

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Abstract Higher intra-individual lap time variation (LTV) of the 400-m walk is cross-sectionally associated with poorer attention in older adults. Whether higher LTV predicts decline in executive function and whether the relationship is accounted for by slower walking remain unanswered. The main objective of this study was to examine the relationship between baseline LTV and longitudinal change in executive function. We used data from 347 participants aged 60 years and older (50.7 % female) from the Baltimore Longitudinal Study of Aging. Longitudinal assessments of executive function were conducted between 2007 and 2013, including attention (Trails A, Digit Span Forward Test), cognitive flexibility and set shifting (Trails B, Delta TMT: Trials B minus Trials A), visuoperceptual speed (Digit Symbol Substitution Test), and working memory (Digit Span Backward Test). LTV and mean lap time (MLT) were obtained from the 400-m walk test concurrent with the baseline executive function assessment. LTV was computed as variability of lap time across ten 40-m laps based on individual trajectories. A linear mixed-effects model

was used to examine LTV in relation to changes in executive function, adjusted for age, sex, education, and MLT. Higher LTV was associated with greater decline in performance on Trails B ($\beta=4.322$, $p<0.001$) and delta TMT ($\beta=4.230$, $p<0.001$), independent of covariates. Findings remained largely unchanged after further adjustment for MLT. LTV was not associated with changes in other executive function measures (all $p>0.05$). In high-functioning older adults, higher LTV in the 400-m walk predicts executive function decline involving cognitive flexibility and set shifting over a long period of time. High LTV may be an early indicator of executive function decline independent of MLT.

Keywords Lap time variation · Executive function · Longitudinal study · Aging

Introduction

In community-dwelling older adults, slower gait is associated with poorer executive function from both cross-sectional (Ble et al., 2005; Doi et al., 2014; Holtzer et al., 2006; Rosano et al., 2005) and longitudinal studies (Inzitari et al., 2007; Mielke et al., 2013). There may be a shared neuropathology underlying the motor and executive deficits. In addition to brain atrophy in the prefrontal and selected subcortical areas (Pugh and Lipsitz, 2002; Roriz-Cruz et al., 2007), white matter lesions and disrupted white matter microstructure (Kuo and Lipsitz, 2004) influence both motor performance and executive function.

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Executive function involves complex processing among cognitive, sensory, and motor systems. There are various constructs within executive function, such as attention, cognitive flexibility and set shifting (Anderson et al., 2001), visuoperceptual speed, as well as working memory (Fisk and Sharp, 2004). Intact executive function is necessary for an individual's independence, even with the loss of other cognitive abilities in older age (Lezak et al., 2004). Thus, executive function is a critical contributor to an older person's quality of life and functional independence. Many aspects of executive function substantially decline at age 60 (Hedden and Gabrieli, 2004; Park et al., 2002). Worsened executive function is associated with subcortical ischemic vascular disease (Jokinen et al., 2009), cerebral microbleeds (Yamashiro et al., 2014), and cerebral microangiopathy (Schroeter et al., 2007). Poorer executive function is also associated with fall risks (Herman et al., 2010; Mirelman et al., 2012) which may lead to subsequent mobility loss and disability. Identifying clinical indicators of executive decline, such as variable and slow gait, may contribute to anticipating cognitive impairment and dementia. A further understanding of the relationship between abnormal gait and executive function is valuable, especially for older adults who have not yet experienced cognitive impairment.

While gait speed is related to executive function, few studies have explored associations of other parameters of gait with executive function, especially among community-dwelling older adults. Abnormal gait, reflected in stride-to-stride variability, may provide prognostic information about worsened neurological processes caused either by age or neuropathological conditions (Beauchet et al., 2013). Greater stride-to-stride gait variability is cross-sectionally associated with poorer global executive function in older adults (Brach et al., 2008; Ijmker and Lamothe, 2012; Martin et al., 2013), and one study shows that greater gait variability is associated with a specific subdomain—information updating and monitoring (Beauchet et al., 2012). One attractive way to measure gait variability is to use fast-paced walking. Fast-paced walking is a stressful and demanding task. Measuring variability during fast-paced walking may address the potential confounding effects of biomechanical abnormalities during usual-paced walking, detects low-functioning individuals, and captures additional physiological differences in fitness and function (Beauchet et al., 2013; Deshpande et al., 2009; Fitzpatrick et al., 2007). Compared to stride-to-stride gait variability, a simpler, more clinically accessible approach is assessing variation

across repeated walking laps (Vestergaard et al., 2009). Our group recently reported that lap time variation (LTV) during a 400-m fast-paced walking was associated with poorer executive function, specifically attention, in the Baltimore Longitudinal Study of Aging (Tian et al., 2015). To control for fatigability, in that study, we defined LTV as variability in lap time based on individual trajectories. The relationship with executive function was not affected by mean lap time, which might have been suggested to play an important role in the relation between LTV and executive function. High LTV under fast-paced walking may potentially indicate a vulnerable stage of central nervous system. LTV may serve as an early and sensitive indicator of poorer executive function decline, but to date, this hypothesis has not been tested in longitudinal studies. Further, it is not clear which constructs within executive function are specifically associated with gait disturbance.

Thus, the objective of this study was to examine the relationship between LTV and longitudinal changes in various constructs of executive function, including attention, cognitive flexibility and set shifting, visuoperceptual speed, and working memory in adults aged 60 and older. We hypothesize that high LTV was prospectively associated with greater rate of decline in executive function. We also hypothesized that the relationship would be independent of mean lap time. To determine the specificity of the findings for executive function/attention, we also examined associations with changes in other cognitive functions (verbal memory, language, and visuospatial ability) and manual dexterity.

Methods

Study population

Participants were drawn from the Baltimore Longitudinal Study of Aging (BLSA). BLSA is a prospective study of community dwellers mostly from the Baltimore–Washington area. BLSA participants aged 60 to 79 return to the National Institute on Aging clinical research unit every 2 years for a variety of clinical, medical, and neuropsychological testing, while participants aged 80 and older return every year for testing.

A total of 813 participants aged 60 and older completed an initial 400-m walk test between 2007 and 2013. Since 1986, participants aged 60 and older in the BLSA completed an expanded neuropsychological

test battery which was used to characterize age-related changes in cognitive function. Of the 813 participants, 349 had at least two measures of executive function conducted between 2007 and 2013. Most also had repeated measures of other cognitive functions (verbal memory, language, and visuospatial ability) and manual dexterity. All cognitive and manual dexterity measures used in the present study were concurrent with and subsequent to the time of the initial 400-m walk test. The follow-up period refers to the time from the initial 400-m walk test to all subsequent assessments of cognitive function. The average number of visits per participant was 2.6 (ranged from 1 to 6).

Based on standardized consensus diagnostic procedures for the BLSA (Driscoll et al., 2006), 347 participants were free of cognitive impairment or dementia at the time of the initial 400-m walk test. Seven of 347 were diagnosed with mild cognitive impairment over the course of the study between 2007 and 2013. As this study focused on normal aging, data of cognitive function at and following the onset of dementia were excluded. Dementia was diagnosed by consensus diagnostic conferences using the Diagnostic and Statistical Manual of Mental Disorders, Third Edition, revised criteria for dementia and the National Institute of Neurological and Communicative Disorders and Stroke–Alzheimer’s disease and Related Disorders Association criteria for Alzheimer’s Disease using neuropsychological diagnostic tests and clinical data (McKhann et al., 1984). The diagnosis of dementia required evidence of a progressive cognitive syndrome, including memory decline.

The study protocol was approved by the institutional review board of record at the time of data collection. All participants provided written informed consent.

Mobility measures

LTV was obtained from the 400-m walk test. Details of the 400-m walk test were described elsewhere (Simonsick et al., 2001). Participants were excluded from the 400-m walk if they had medical contraindications (Newman et al. 2006). Briefly, participants were instructed to walk for ten 40-m laps as quickly as possible and they received feedback and encouragement after completion of each lap. Participants may not be able to complete the entire ten laps due to fatigue or symptoms. Lap time was recorded after the completion of each lap using a stop watch by an examiner. For those who completed the 400-m walk, LTV was calculated as standard deviation of lap

time residuals based on individual trajectories (Tian et al., 2015). First, an individual trajectory of lap time across ten laps was computed for each participant. Second, an estimated lap time at each lap was computed based on the individual trajectory. The residual was obtained by subtracting the actual lap time from the estimated lap time. Then the standard deviation of the residuals was obtained as LTV. This measure accounted for the possible effect of fatigability as the lap number increased (Simonsick et al., 2014; Tian et al., 2015). Mean lap time was obtained as the average of lap time across ten laps.

Usual gait speed was measured on a 6-m course in an uncarpeted corridor. Participants were asked to walk at their usual and comfortable pace. Time to complete the 6-m course was measured. Two trials were completed and the faster gait speed was used in the study in meter/s.

Cognitive and manual dexterity measures

Executive function, other cognitive functions (verbal memory, language, and visuospatial ability), and manual dexterity were assessed by trained examiners. It was expected to see that LTV was associated only with longitudinal change in executive function and not with changes in verbal memory, language, visuospatial ability, or manual dexterity.

Executive function was measured by a variety of neuropsychological tests, including the Trail Making Test (TMT), the Digit symbol substitution test (DSST), and the Digit Span Test. Specifically, attention and motor speed were assessed by Trails A and Digit Span Forward Test provided another measure of attention and concentration (Lezak, 1995). Cognitive flexibility and set shifting was assessed by the Trails B and Delta TMT (i.e., Trails B minus Trails A) (Kortte et al., 2002; Lezak, 1995). Visuospatial speed was assessed by the DSST (Wechsler, 1981). Working memory was assessed by the Digit Span Backward Test (Wechsler, 1981).

Verbal memory was measured by the California Verbal Learning Test (Delis, 1991) and Benton Visual Retention Test, respectively (Benton, 1965). Language and verbal fluency were measured by the letter (Thurstone, 1938) and category fluency test (Rosen, 1980). Visuospatial ability was measured by the card rotation test (Ekstrom et al., 1976). Manual dexterity was assessed by the Purdue Pegboard Test (Tiffin, 1968), and it was included in this study because it required sensorimotor function.

Statistical analysis

Bivariate associations between sample characteristics and LTV were examined using the Pearson correlation coefficients or independent *t* tests as appropriate. Bivariate associations between baseline executive function measures and LTV were examined using the Pearson correlation coefficients. Associations between LTV and changes in executive function, other cognitive functions, and manual dexterity were examined using the linear mixed-effects model which accounted for repeated measures (SAS v. 9.3; SAS Institute, Cary, NC).

The model was first adjusted for age, sex, education, and body mass index. Each cognitive measure was modeled as a dependent variable. LTV, interval (i.e., the time period in years between baseline cognitive measurement and each follow up visit), baseline age, sex, education, and their interaction with interval were modeled as fixed effects. The intercept and interval were modeled as random effects. The full model was set up as: cognitive measure = $\beta_0 + \beta_1 \times \text{LTV} + \beta_2 \times \text{interval} + \beta_3 \times \text{LTV} \times \text{interval} + \beta_4 \times \text{age} + \beta_5 \times \text{sex} + \beta_6 \times \text{education} + \beta_7 \times \text{age} \times \text{interval} + \beta_8 \times \text{sex} \times \text{interval} + \beta_9 \times \text{education} \times \text{interval} + \beta_{10} \times \text{body mass index} + \beta_{11} \times \text{body mass index} \times \text{interval}$.

To examine whether walking speed would affect the relationship, the model was further adjusted for mean lap time and its interaction with interval. The adjusted

model was set up as: cognitive measure = $\beta_0 + \beta_1 \times \text{LTV} + \beta_2 \times \text{interval} + \beta_3 \times \text{LTV} \times \text{interval} + \beta_4 \times \text{age} + \beta_5 \times \text{sex} + \beta_6 \times \text{education} + \beta_7 \times \text{age} \times \text{interval} + \beta_8 \times \text{sex} \times \text{interval} + \beta_9 \times \text{education} \times \text{interval} + \beta_{10} \times \text{body mass index} + \beta_{11} \times \text{body mass index} \times \text{interval} + \beta_{12} \times \text{mean lap time} + \beta_{13} \times \text{mean lap time} \times \text{interval}$.

In the linear mixed-effects model, the regression coefficient of LTV represented the cross-sectional association between LTV and baseline cognitive functions and manual dexterity. The regression coefficient of the interaction between LTV and interval represented longitudinal associations between LTV and changes in cognitive functions and manual dexterity during follow-up.

Although most had more than one cognitive function measures during follow-up, we conducted a sensitivity analysis by excluding those who had only one baseline assessment (Digit Span Tests: $n=345$; Purdue Pegboard Test dominant hand: $n=337$; non-dominant hand: $n=335$; CVLT immediate free recall: $n=343$; CVLT long-delay free recall: $n=343$; CVLT short-delay free recall: $n=342$; BVRT: $n=345$; Card Rotation Test: $n=342$).

Results

Table 1 describes baseline sample characteristics and mobility measures. Higher LTV was associated with

Table 1 Baseline sample characteristics and their correlations with lap time variation (LTV) ($n=347$)

	Mean $\pm$ SD or <i>N</i> (%)	Range	Correlations with LTV: <i>r</i> (<i>p</i> value) or MD $\pm$ SE (<i>p</i> value)
Demographics			
Age, years	70.7 $\pm$ 7.7	60.0–94.7	0.233 (<0.001)
Female	176 (50.7)	–	0.05 $\pm$ 0.04 (0.263)
Education>college	193 (55.6)	–	–0.02 $\pm$ 0.04 (0.593)
Black	101 (29.1)	–	0.01 $\pm$ 0.05 (0.856)
Height, cm	169.6 $\pm$ 8.9	149.4–194.9	–0.139 (0.009)
Weight, kg	78.1 $\pm$ 15.0	44.7–149.6	0.034 (0.532)
Health-related conditions			
Current smokers or quit<10 years	12 (3.5)	–	0.03 $\pm$ 0.12 (0.803)
Moderate-to-vigorous activity>150 min/week	138 (39.8)	–	–0.10 $\pm$ 0.04 (0.014)
Body mass index, kg/m ²	27.1 $\pm$ 4.4	18.3–45.7	0.132 (0.014)
Usual gait speed, meter/s	1.17 $\pm$ 0.20	0.44–1.73	–0.271 (<0.001)
Mobility measures			
Lap time variation, s	0.8 $\pm$ 0.4	0.2–4.1	–
Mean lap time, s	27.0 $\pm$ 5.1	18.0–57.7	0.418 (<0.001)

MD $\pm$ SE denotes mean difference $\pm$ standard error

older age and shorter height. Those who reported less than 150 min per week moderate to vigorous exercise had higher LTV than those who reported more. Higher body mass index, longer mean lap time, and slower usual gait speed were associated with higher LTV. Other sample characteristics, such as sex, race, education, body weight, and smoking status, were not associated with LTV. Table 2 describes baseline values of executive function, other cognitive functions, and manual dexterity. Bivariate analysis of baseline data showed that higher LTV was correlated with poorer performance on the Trails A, DSST, Purdue Pegboard Test, BVRT, and Card Rotation Test (Table 2). Bivariate associations between LTV and other cognitive function measures were not significant (Table 2).

After adjustment for age, sex, education, and body mass index, the cross-sectional association between LTV and Trails A remained significant (Table 3, cross-sectional, model 1). This association persisted after

further adjustment for mean lap time (Table 3, cross-sectional, model 2). Cross-sectional associations of LTV with other cognitive function measures or manual dexterity were not significant after adjustment for age, sex, education, body mass index, and mean lap time (Table 3, cross-sectional, model 1 and 2).

Higher LTV was prospectively associated with greater decline in performance on the Trails B and Delta TMT during follow-up, after adjustment for age, sex, education, and body mass index (Table 3, longitudinal, model 1; Fig. 1). These associations remained significant after further adjustment for mean lap time (Table 3, longitudinal, model 2). LTV was not associated with changes in other executive function measures or with changes in manual dexterity, verbal, language, and visuospatial ability (Table 3, longitudinal).

Results remained largely unchanged when analyses were restricted to participants with repeated cognitive assessments during follow-up (data not shown).

Table 2 Measures of executive function, other cognitive functions, and manual dexterity ($n=347$)

Measures		Total number of visits	Repeat visits, Mean $\pm$ SD range	First visit, mean score	Correlations with LTV, r (p value)
Executive function (hypothesized domain)	Attention				
	Trails A, s	953	2.7 $\pm$ 0.8 (2-6)	31 $\pm$ 10	0.252 (<0.001)
	Digit span forward	944	2.7 $\pm$ 0.8 (1-6)	8.3 $\pm$ 2.4	0.014 (0.789)
	Cognitive flexibility and set shifting				
	Trails B, s	953	2.7 $\pm$ 0.8 (2-6)	76 $\pm$ 32	0.084 (0.116)
	Delta TMT, seconds	953	2.7 $\pm$ 0.8 (2-6)	45 $\pm$ 28	0.003 (0.949)
	Visuoperceptual speed				
	Digit symbol substitution test	925	2.7 $\pm$ 0.8 (2-5)	48 $\pm$ 10	-0.148 (0.006)
Other cognitive functions and manual dexterity	Working memory				
	Digit span backward	945	2.7 $\pm$ 0.8 (1-6)	7.1 $\pm$ 2.4	-0.070 (0.197)
	Verbal memory				
	CVLT immediate free recall (sum of 5 trials)	927	2.7 $\pm$ 0.8 (2-6)	53.7 $\pm$ 11.5	-0.041 (0.453)
	CVLT long-delay free recall	925	2.7 $\pm$ 0.8 (1-6)	10.9 $\pm$ 3.2	-0.035 (0.522)
	CVLT short-delay free recall	922	2.7 $\pm$ 0.8 (1-6)	11.5 $\pm$ 3.3	-0.047 (0.385)
	BVRT	943	2.7 $\pm$ 0.8 (1-6)	5.9 $\pm$ 3.9	0.139 (0.010)
	Language				
	Letter fluency	953	2.7 $\pm$ 0.8 (2-6)	14.6 $\pm$ 4.1	-0.049 (0.364)
	Category fluency	953	2.7 $\pm$ 0.8 (2-6)	16.4 $\pm$ 3.6	-0.109 (0.042)
	Visuospatial ability				
	Card rotation	919	2.6 $\pm$ 0.8 (1-6)	93.8 $\pm$ 40.0	-0.129 (0.017)
	Manual dexterity				
	Pegboard dominant	919	2.6 $\pm$ 0.8 (2-5)	12.2 $\pm$ 1.8	-0.161 (0.003)
	Pegboard non-dominant	898	2.6 $\pm$ 0.8 (2-5)	11.9 $\pm$ 1.7	-0.117 (0.032)

LTV lap time variation, Delta TMT Trails B minus Trails A, CVLT California verbal learning test, BVRT Benton visual retention test

Table 3 Associations between lap time variation (LTV) and changes in executive function, other cognitive functions, and manual dexterity ($n=347$)

	Cross-sectional: LTV		Longitudinal: LTV $\times$ interval	
	Model 1 β (SE), p value	Model 2	Model 1 β (SE), p value	Model 2
Attention				
Trails A	4.563* (1.489) 0.002	3.487* (1.540) 0.024	0.041 (0.334) 0.902	-0.243 (0.350) 0.489
Digit span backward	-0.204 (0.315) 0.518	-0.129 (0.331) 0.698	-0.069 (0.081) 0.399	-0.070 (0.086) 0.412
Cognitive flexibility and set shifting				
Trails B	-0.781 (4.822) 0.872	-4.202 (5.040) 0.405	5.701* (1.124) <0.001	5.758* (1.185) <0.001
Delta TMT	-5.263 (4.145) 0.205	-7.532 (4.353) 0.085	5.680* (1.135) <0.001	6.002* (1.196) <0.001
Visuoperceptual speed				
Digit symbol substitution test	-1.384 (1.246) 0.267	-0.369 (1.297) 0.777	-0.093 (0.220) 0.673	-0.120 (0.232) 0.606
Working memory				
Digit span forward	0.231 (0.327) 0.481	0.309 (0.344) 0.370	-0.081 (0.082) 0.324	-0.127 (0.086) 0.139
Verbal memory				
CVLT immediate free recall	0.127 (1.548) 0.935	0.959 (1.622) 0.555	0.085 (0.345) 0.806	0.221 (0.363) 0.542
CVLT long-delay free recall	0.089 (0.437) 0.839	0.200 (0.459) 0.664	0.021 (0.094) 0.822	0.088 (0.099) 0.373
CVLT short-delay free recall	0.116 (0.434) 0.790	0.284 (0.455) 0.533	-0.049 (0.094) 0.603	-0.045 (0.099) 0.648
BVRT	0.451 (0.471) 0.339	0.352 (0.494) 0.477	0.104 (0.110) 0.345	0.074 (0.115) 0.522
Language				
Letter fluency	-0.588 (0.535) 0.273	-0.217 (0.558) 0.698	-0.060 (0.090) 0.502	-0.015 (0.094) 0.876
Category fluency	-0.166 (0.451) 0.713	0.262 (0.469) 0.577	-0.003 (0.082) 0.972	-0.009 (0.087) 0.919
Visuospatial ability				
Card Rotations	-3.196 (5.137) 0.534	-0.537 (5.379) 0.921	-0.987 (0.696) 0.157	-0.828 (0.734) 0.259
Manual dexterity				
Pegboard dominant	-0.117 (0.186) 0.549	0.174 (0.189) 0.357	-0.027 (0.047) 0.562	-0.029 (0.049) 0.560
Pegboard non- dominant	-0.022 (0.191) 0.910	0.217 (0.197) 0.272	0.019 (0.048) 0.685	0.017 (0.050) 0.733

Model 1: adjusted for age, sex, education, body mass index, and their interaction with interval

Model 2: model 1+mean lap time+mean lap time $\times$ interval

* $p<0.05$, significant associations

Discussion

Among high-functioning older adults, higher LTV predicts a greater rate of decline in executive function specifically involving cognitive flexibility and set shifting. We did not find associations with changes in other executive function measures, verbal memory, language, visuospatial ability, or manual dexterity.

This study extended previous research by examining longitudinal patterns of executive function and gait disturbance. The link between executive function and LTV in this study is in line with previous cross-sectional

findings (Brach et al., 2008; Ijmker and Lamoth, 2012; Martin et al., 2013; Tian et al., 2015). Initial neuroimaging studies support the notion that poor motor and executive functions share a common neuropathology (Bolanzadeh et al., 2014; Nadkarni et al., 2014; Rosano et al., 2012). Among various subdomains of executive function, we observed a strong association between LTV and declines in cognitive flexibility and set shifting, captured by the Trails B and Delta TMT. The Trails B requires alternating attention and mental tracking between tasks and contains a working memory component. Delta TMT adjusts for the motor speed

Fig. 1 Predicted values of Trails A (a), Trails B (b), and Delta TMT (c) as a function of follow-up time, stratified by tertiles of baseline lap time variation

component and provides a clearer index of cognitive flexibility and set shifting than the Trails B alone. The ability to alternate attention and switch tasks is essential for daily performance, such as walking while talking, watching TV while making dinner. Intact cognitive flexibility and set shifting is critical for walking and is related to fall risks.

We are aware that prior studies also showed associations of gait variability with manual dexterity (Brach et al., 2008), visuospatial ability (Martin et al., 2013), and memory (Li et al., 2001). The fact that we did not observe associations of LTV with these factors may be due to different measures of gait parameters, different study populations, and with or without accounting for the effect of walking speed. For instance, double-support phase variability was shown to be associated with visuospatial ability (Martin et al., 2013). Visuospatial ability influences postural control which may alter double-support phase variability. Another study showed stance time variability was shown to be associated with manual dexterity measured by finger tapping, without consideration of walking speed (Brach et al., 2008). This relationship was found only in slow walkers, but not in fast walkers.

The observed associations were robust, independent of walking speed. Some prior studies focusing on gait variability and executive function did not consider the influence of walking speed. Mounting evidence shows slower gait is associated with poorer executive function both cross-sectionally and longitudinally. In the present study, walking speed was highly correlated with LTV. Thus, it is important to account for walking speed because it is related to both the predictor and the outcome. Further, we hypothesize that variable gait may precede overall slowing, not vice versa. Prior research suggests that slow walking is more likely to be the consequence of variable walking (Kang and Dingwell, 2008). Thus, it is essential to understand whether LTV is an early indicator of executive decline, independent of walking speed. After accounting for walking speed, our results remained largely unchanged. This suggests that LTV may be an independent, early indicator of executive decline over time.

One novel aspect of the study is the use of a measure of LTV. LTV is simple to measure and clinically accessible and has several advantages. Compared to conventional stride-to-stride gait variability, LTV is easy to

implement in large population-based studies and clinical settings with low cost. It does not require a motion analysis system or force plate. Further, LTV is informative, high levels of which predict mortality (Vestergaard et al., 2009). As fatigue might cause progressive slowing across laps, a simple standard deviation would not account for decreased trend toward slowing, which is not the same as variability. LTV was calculated around individual trajectories in our study. Compared to the measure of lap time variability used in the prior study (Vestergaard et al. 2009), our approach accounted for fatigability and more accurately reflects intra-individual variations in motor performance. It is worth noting that LTV is measured under fast-paced walking, which requires maximal effort. The added stress allows it well, characterizing individuals with low physical function. This approach reduces the potential biomechanical effects during usual-paced walking. It would be interesting to investigate LTV under different speeds and distances in relation to executive decline in future research.

This study has limitations. The study sample is composed of high-functioning elderly limited to those who can complete the 400-m walk test. Participants in the BLSA tend to be very healthy compared to general population. Findings may not be generalizable to a broader population including those with mobility and cognitive impairments. Further, findings from this study do not imply any causal relationship between motor and executive deficits. While we observed LTV was associated with changes in executive function over time, a possible reverse causation cannot be ruled out. It is still not known whether motor deficit predicts the subsequent executive deficit, or vice versa. Future studies are warranted to examine the temporal sequence of motor and executive functions in a contemporary period.

In conclusion, high-functioning older adults with higher LTV may have greater decline in executive function, primarily involving cognitive flexibility, and set shifting. LTV may be used in a clinical context as an important early indicator of executive decline for older adults.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no competing interests.

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