

Cognitive Processes Related to Gait Velocity: Results From the Einstein Aging Study

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The authors examined the relationship between cognition and gait velocity, performed with and without interference, in elderly participants. Neuropsychological test scores from 186 cognitively normal elders were submitted to factor analysis that yielded 3 factors: Verbal IQ, Speed/Executive Attention, and Memory. Regression analyses revealed that these factors were significant predictors of variance in gait velocity, but the relationship varied as a function of task condition. All 3 factors predicted gait velocity without interference. However, the Speed/Executive Attention and Memory factors but not Verbal IQ predicted gait velocity in the interference condition. These findings suggest that gait velocity and cognitive function may have both shared and independent brain substrates. Future studies should explore gait velocity and cognitive function as predictors of dementia and falls.

Keywords: aging, cognition, gait velocity

Cross-sectional and prospective studies found a relationship between cognitive status and functional activity in the elderly (Barberger-Gateau & Fabrigoule, 1997). Findings from a large-scale prospective study of aging further suggested that cognitive decline is associated with a specific pattern of loss of functional activity (Njegovan, Man-Son-Hing, Mitchell, & Molnar, 2001). Instrumental activities of daily living (e.g., managing finances) are lost earlier than are basic activities of daily living such as walking. Although the absence of gait and balance problems predicted functional independence (Perrault, Wolfson, Egan, Rockwood, & Hogan, 2002), the presence of gait disorder and its severity were both related to increased risk of death (Wilson, Schneider, Beckett, Evans, & Bennet, 2002). Moreover, two recent studies found that engaging in physical activity such as walking is associated with a lower risk of dementia in elderly men (Abbott et al., 2004) and women (Weuve et al., 2004).

However, a relatively limited number of studies examined the interplay between cognitive processes and gait (Barberger-Gateau

et al., 1997; Chen et al., 1996; Lajoie, Teasdale, Bard, & Fleury, 1996; Li, Linderberger, Freund, & Baltes, 2001; Linderberger, Marsiske, & Baltes, 2000; Sparrow, Bradshaw, Lamoureux, & Tirosh, 2002) or posture control (Brauer, Woollacott, & Shumway-Cook, 2001; Brown, Shumway-Cook, & Woollacott, 1999; Maylor, Allison, & Wing, 2001; Maylor & Wing, 1996; Redfern, Muller, Jennings, & Furman, 2002; Shumway-Cook, Woollacott, Kerns, & Baldwin, 1997; Teasdale, Bard, LaRue, & Fleury, 1993) in aging. The above referenced studies often relied on dual-task methodology, involving simultaneous performance of cognitive and motor tasks, in order to examine the relationship between cognition and walking or posture control. This choice of experimental approach is not surprising given that attentional resources that decline with age (Craig & Byrd, 1982) are required for maintaining one's posture and gait, especially in public where the ability to negotiate competing/interfering demands from the environment is paramount. Dual-task methodology provides a theoretical and empirical basis for evaluating divided attention (Baddeley, 1996; Baddeley & Hitch, 1974) as well as experimental control over the extent of the attentional demands required for task completion. Furthermore, the effect of aging on dual-task performance has been studied extensively (Hartley, 1992; McDowd & Shaw, 2000) and evaluated by using meta-analytic procedures (Verhaeghen, Steitz, & Cerella, 2003; Verhaeghen & Cerella, 2002). Hence, relying on this methodological approach to examine the interplay between cognitive processes and gait is consistent with a large corpus of cognitive experimental research. Indeed, a consistent finding in the studies referenced earlier was that dual-task costs were greater in old relative to young individuals, suggesting that limited attention was related to impaired gait and postural performance in aging.

However, knowledge concerning the relationship between cognition and gait in aging has been limited by several factors. The majority of the studies compared dual-task performance in relatively small samples of young and old individuals. In that context, age-related dual-task costs were used to infer that limited attention was related to lower gait performance in old persons. However,

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recent studies suggest that compromised executive control may underlie the negative effect of aging on dual-task performance involving other cognitive–motor tasks (Holtzer, Stern & Rakitin, 2004, 2005). Hence, it is of interest to examine whether executive processes are related to gait performance, in cognitively normal elders, when gait is evaluated with and without a secondary cognitive interference task.

The structural correlates of cortical gait control have not been well established. Independent studies have shown that poor balance and abnormal gait are related to atrophy in the temporal lobe (Guo et al., 2001) and frontal lobe (Kerber, Enrietto, Jacobson, & Baloh, 1998) in elderly persons. In addition, mobility impairments in elderly persons are related to periventricular white matter abnormality as evident from cross-sectional (Benson et al., 2002), prospective (Whitman, Tang, Lin, & Baloh, 2001), and neuro-pathological (Whitman et al., 1999) studies.

As indicated above, gait is multifactorial in terms of its underlying cortical control mechanisms, which gives rise to the possibility that separate cognitive processes are differentially related to gait performance. Specifically, the cortical correlates of gait would suggest that speed, executive control, and memory may be necessary for successful walking. Establishing relationships between gait performance and distinct cognitive processes may also help identify functional neural networks that are shared by covert cognitive processes and overt motor outcomes.

Hence, motivation for this study was fourfold: First, given the limited literature concerning the relationship between gait and cognitive function and the almost exclusive focus on attention, we examined the importance of additional cognitive processes in explaining age-related variance in gait performance. Second, separate cognitive processes may be differentially related to gait performance as a function of whether distracting or competing stimuli are introduced when a person is walking. That is, it is reasonable to suggest that the cognitive demands of gait will vary depending on whether a person walks in a quiet environment or when negotiating the concomitant demands of competing visual or verbal stimuli. Third, differential relationship of separate cognitive processes with gait may provide important insight with respect to functional networks shared by distinct cognitive functions and gait. Fourth, because gait velocity is predictive of falls, characterizing the cognitive mechanisms of gait velocity may in turn provide important information concerning the risk assessment and possible treatment and/or prevention of falls. Characterizing the relationship between cognitive function and gait in aging requires comprehensive neuropsychological assessment of multiple cognitive domains. Furthermore, empirical derivation of statistically independent cognitive–neuropsychological factors is important when addressing the question of whether separate cognitive abilities are independently related to gait.

Gait is complex and multifactorial in terms of its underlying control mechanisms. Velocity is the most common quantitative performance index used in the gait literature. Moreover, the different gait measures relate to function and integrity of various parts of the nervous system such as the frontal subcortical regions, basal ganglia, cerebellum, and peripheral nerves. This article concentrates on gait velocity in order to maintain consistency with the current literature and to facilitate future comparisons.

Current Study

We hypothesized that general level of cognitive function (e.g., IQ) as well as specific cognitive abilities that are sensitive to the aging process, in addition to attention (e.g., memory), would predict gait velocity. We further hypothesized that the relationship between separate cognitive abilities and gait would vary when a secondary verbal task was added to the gait task.

To accomplish the aims of the study, we developed a set of carefully operationalized and statistically independent cognitive factors and examined their relationships with gait velocity in a large sample of healthy elders. Because gait is multifaceted in terms of its presumed underlying contributory factors, we have initiated a three-phase approach. First, we evaluated whether general (Verbal IQ) and specific (Speed/Executive Attention) cognitive factors were related to gait velocity. Second, we examined whether the general and specific cognitive factors remain significant predictors of gait velocity after controlling for the effect of noncognitive factors. Third, we determined whether the cognitive and noncognitive factors were differentially related to gait velocity performed with and without a secondary verbal interference task (Vergheze, Buschke, et al., 2002; see following *Method* section for details).

Method

Participants

Participants of the current study were also participants in the Einstein Aging Study (EAS), a longitudinal aging study. The EAS has used telephone-based screening procedures to recruit and follow a community-based cohort since 1999 (Lipton et al., 2003; Vergheze et al., 2004). The primary aim is to identify risk factors for dementia. Eligibility criteria are age 70 and over, residing in Bronx, and English speaking. Exclusion criteria include severe audiovisual disturbances that would interfere with completion of neuropsychological tests, inability to ambulate even with a walking aid or in a wheelchair, or institutionalization. Potential participants over age 70 from the Center for Medicaid and Medicare Services population lists of Medicare eligible individuals were first contacted by letter, and then by telephone, explaining the purpose and nature of the study. The telephone interview included verbal consent, a brief medical history questionnaire, and telephone-based cognitive screening tests (Lipton et al., 2003). Following the interview, participants who met eligibility criteria over the phone were invited for further screening and evaluations at our clinical research center. Following the in-person evaluation, 488 participants were enrolled between 1999 and 2001. Informed consents were obtained at clinic visits according to study protocols approved by the local institutional review board. Participants were followed at yearly intervals.

Quantitative gait evaluations were introduced at the EAS in 2001. Of the 488 participants, 223 (46%) received quantitative gait assessments between 2001 and 2004. For the purposes of this study, we excluded 22 participants who met criteria for mild cognitive impairment (MCI; Petersen et al., 1999, 2001)) and 15 who met criteria for dementia (McKhann et al., 1984) at the time of their gait evaluation as determined at the EAS consensus diagnostic case conferences. A total of 186 elderly, cognitively normal community residents were eligible to participate in the present study.

Measures

Neuropsychological tests. The neuropsychological test battery was selected to assess premorbid and current level of cognitive status, speed of processing, attention, memory, language, and executive function. The

specific tests that were included in the battery have been validated for use in both normal aging and in dementia in numerous prospective and cross-sectional studies in our center.

The following tests were included in the neuropsychological battery: The Information, Vocabulary, Digit Span, Digit Symbol, and Block Design tests from the Wechsler Adult Intelligence Scale—Revised (WAIS-R; Wechsler, 1981) and the Wechsler Adult Intelligence Scale—III (WAIS-III; Wechsler, 1997); a 15-item, abbreviated version of the Boston Naming Test (BNT; Stern et al., 1992); free recall from the Free and Cued Selective Reminding Test (FCSRT; Grober, Buschke, Crystal, Bang, & Dresner, 1988; Buschke, 1973); the Trails Making Test (Forms A and B; Lezak, 1995); and the Letter and Category Fluency tests (FAS; Lezak, 1995).

Quantitative gait assessment. Research assistants conducted quantitative gait evaluations independent of the clinical evaluation. Quantitative gait variables were collected by using a 12-ft computerized gait mat ($180 \times 35.5 \times 0.25$ in.) with embedded pressure sensors (GAITRite, CIR systems, Havertown, PA). Excellent reliability and validity for GAITRite assessments were reported in previous research in our center (Verghese, Buschke, et al., 2002) and in other studies (Bilney, Morris, & Webster, 2003). The quantitative gait assessment provides several parameters. However, for this analysis, for the sake of simplicity and comparability with prior work, we focused on gait velocity, the most commonly used metric in gait research. *Velocity* (cm/s) is obtained by dividing the distance covered on three trials by the ambulation time. *Step length* (cm) is measured from the heel point of the current footfall to the heel point of the previous footfall on the opposite foot. Cadence is the number of steps taken in a minute. *Stride length* (cm) is the distance between the heel points of two consecutive footfalls of the same foot (left to left, right to right). Stride length variability was calculated by determining the standard deviation and the coefficient of variation (CV) of each participant's stride length (Danion, Varraine, Bonnard, & Philhous, 2003). The CV is calculated as $100 \times SD/M$. Gait variability has previously been associated with gait unsteadiness and a significant risk for falls (Hausdorff, Rios & Edelberg, 2001). Double support is the time (in s) elapsed between first contact of the current footfall and the last contact of the previous footfall, added to the time elapsed between the last contact of the current footfall and the first contact of the next footfall.

Walking protocol. At baseline, (alone condition) participants were asked to walk on the mat in a well-lit hallway at their "normal walking speed" for three trials. Start and stop points were marked by white lines on the floor and included 3 ft each for initial acceleration and terminal deceleration. Monitoring devices were not attached to the participants during the test. Using protocols developed and validated with another sample (Verghese, Buschke, et al., 2002), we then asked the present participants to walk the course for three additional trials while reciting alternate letters of the alphabet (interference condition). To improve reliability and validity, we switched to quantitative measurements and excluded turns from our original protocol (Verghese, Buschke, et al., 2002), which are a known source of variability (Bootsma-vander Wiel et al., 2003). To reduce learning effects, participants were given practice trials on both the single and dual tasks to familiarize themselves with the procedure. The order of the initial letter on the interference task was randomly varied between A and B to minimize practice effects.

Clinical gait assessment. Structured clinical evaluations were done at each visit by study clinicians who determined whether gaits were normal or abnormal (Verghese, Lipton, et al., 2002, 2004). Abnormal gaits were classified as either non-neurological (resulting from causes such as arthritis or cardiac disease) or neurological (unsteady, ataxic, frontal, Parkinsonian, neuropathic, hemiparetic, and spastic) by using previously described methods (Verghese, Lipton, et al., 2002). Abnormal gaits were classified as "combined" if it resulted from both neurological and non-neurological causes in the judgment of the clinician. Abnormalities were graded as mild (walks without assistance), moderate (uses walking aid such as cane), or severe (wheelchair or stands only with assistance). A previous study

reported 89% agreement ($\kappa = .60$) on gait evaluations done 1 year apart in 189 participants in the Bronx Aging Study (Verghese, Lipton, et al., 2002). Our prospective comparisons of gait assessments done by junior and senior clinicians in 30 EAS participants also showed high reliability ($\kappa = .80$) (Verghese et al., 2004).

Total disease score. Dichotomous rating of the following conditions was used to calculate a summary score of disease comorbidity: diabetes, hypertension, chronic heart failure, myocardial infarction, chronic obstructive lung disease, depression, stroke, Parkinson's disease, and arthritis.

Statistical Analyses

Factor analysis of the neuropsychological tests. For data reduction purposes, neuropsychological raw test scores were submitted to principal components factor analysis (PCA; Bryant & Yarnold, 1995). Because the PCA was run on the correlation matrix, the raw scores were normalized based on the distribution of the entire sample. Varimax rotation was used to derive orthogonal factor scores, and the minimum eigenvalue for extraction was set at 1.

Prediction of gait velocity. Multiple linear regression analyses examined whether individual differences on the neuropsychological factors predicted gait velocity performance variance in the alone and the interference conditions. The neuropsychological factor scores served as predictors that were entered in one block. Demographic variables (gender, age, education) and a comorbidity disease index were entered in a second block to examine whether inclusion of these variables added to the prediction of velocity variance in the model. Moreover, it was of interest to examine whether the contribution of the neuropsychological factors to the prediction of gait velocity remained significant after controlling for the effect of the noncognitive variables. Initially, ethnicity and wave of quantitative gait assessment were included in the regression model as well. However, because these two variables were not significant in any of the regression models, they were excluded from the final analyses. Clinical diagnosis of abnormal gait was entered as an additional predictor in a third block. Although the relation of clinical diagnosis of gait to velocity was intuitively assumed, including clinical gait abnormality as an additional covariate served as the most stringent test for the relationship between the neuropsychological factors and gait velocity. In the second and third blocks, the cognitive factors and the other noncognitive covariates were entered simultaneously. Hence, the regression coefficients of the cognitive factors were adjusted for age, education, gender, and disease status in Block 2 and for clinical gait abnormality in Block 3 as well. Velocity indices in the alone and interference conditions served as the criteria in separate regression models. As judged by the histograms, the normality assumption for the velocities did not appear to be violated. The magnitude of the standardized beta coefficients was used to evaluate the relative contribution of each predictor to the variance of the dependent measures. All analyses were conducted with SPSS (Version 12; SPSS Incorporated, 2003).

Results

Sample Characteristics

Demographic characteristics, neuropsychological test scores and gait velocity performance indices for the entire sample are summarized in Table 1.

Table 1 reveals balanced gender distribution and mean education level that exceeds high school diploma. Blessed performance was indicative of functional independence. The total disease score indicates that the participants in this study were relatively healthy (see dependent measures for details). Of the 186 participants, 73 (39.2%) were diagnosed with abnormal gait following evaluation

Table 1
Descriptive Statistics of Demographic Variables, Neuropsychological Tests (Raw Scores), and Velocity in the Alone and the Interference Conditions for the Entire Sample (N = 186)

Variable	M	SD
Age (years)	78.00	4.50
Education (years)	14.30	3.30
Gender (%)		
Female	56.50	
Male	43.40	
Total Disease Score	1.80	1.20
Gait abnormality ^a (%)	39.00	
BDRS (total score)	1.80	1.90
Information (total score)	22.60	5.70
Vocabulary (total score)	49.50	12.60
BNT (15-word version)	12.20	2.40
FAS (total score)	37.80	12.40
FCSRT	33.80	4.40
Category Fluency	39.30	8.70
Digit Span (total score)	13.50	3.80
Block Design (total score)	19.30	8.80
Digit Symbol (total score)	38.40	10.80
Trails A (time in s)	56.40	22.70
Trails B (time in s)	130.80	59.20
Trails B (error)	1.70	3.20
Velocity–Alone (cm/s)	97.00	23.60
Velocity–Interference (cm/s)	77.70	24.40

Note. BNT = Boston Naming Test; FAS = Verbal Fluency; FCSRT = Free and Coed Selective Reminding Test; BDRS = Blessed Dementia Rating Scale.

^a Clinical diagnosis of gait abnormality was determined according to standardized published criteria and independent of the neuropsychological test scores and quantitative gait assessments.

by the study clinicians. The severity of the clinical gait abnormality was rated mild in 49 participants (67.1%), moderate in 23 participants (31.5%), and severe in 1 participant (1.3%). The gait abnormality was subtyped as neurological in 29 participants (39.7%), non-neurological in 33 participants (45.2%), and combined in 11 participants (15.1%). As expected, gait velocity was lower in the interference compared with the alone condition

Table 2 provides a summary of velocity and other quantitative gait parameters of normal walking for the entire sample and as a function of clinical diagnosis of gait abnormality.

As expected, inspection of Table 2 reveals that clinical diagnosis of gait abnormality has a significant negative effect on gait velocity and all other quantitative gait parameters.

Factor Analysis—Neuropsychological Tests

A PCA of the neuropsychological test scores yielded exactly three significant orthogonal factors (minimum eigenvalue for extraction was set at 1) that accounted for a total of 61% of the variance in test scores (see Table 3).

The loading coefficients of the neuropsychological tests on the three factors were consistent with their purported use in the literature. The Verbal IQ factor consisted of the Information, Vocabulary, BNT, FAS, and Digit Span tests. The Verbal IQ factor captured a fairly broad base of verbal abilities that vary in terms of

their sensitivity to age-related cognitive changes. As such, this factor should not be considered as a measure of premorbid and relatively stable measure of IQ.

The Speed/Executive Attention factor consisted of the Trails Form A (time)¹ and Form B (time and errors), Block Design, and Digit Symbol. These timed tests of attention, problem-solving skills and executive function all rely on processing speed. Hence, the relationship between this factor and the outcome variables must be interpreted in the context of shared dependence on speed of processing. The Memory factor consisted of the FCSRT and Category Fluency test scores. The FCSRT is a commonly used test of verbal memory. The Category Fluency test requires retrieval of words from semantic memory. Combined, these two tests provide a sound Verbal Memory factor.

Multiple Linear Regression Analyses—Prediction of Gait Velocity

The three neuropsychological factors, demographic variables, comorbidity index, and presence of clinical gait abnormality were used as predictors in two separate regression analyses, with velocity indices in the alone and the interference conditions serving as the dependent measures. Summary of the results of these analyses is presented in Table 4.

The neuropsychological factors were significant predictors of velocity in the alone condition explaining 16% of the variance. Inclusion of the demographic variables explained an additional 10% of the variance, and clinical diagnosis of gait abnormality added 14% to the explained variance.²

The neuropsychological factors were also significant predictors of velocity in the interference condition accounting for 15% of the variance. The demographic variables, which were marginally significant, explained an additional 5% of the variance and the clinical diagnosis of gait abnormality added 16% to the explained variance.

Table 5 reveals that the neuropsychological factors were significant predictors of velocity in the alone condition. With the exception of gender, all other demographic variables were significantly related to velocity as well. As expected, gait abnormality was a significant predictor of velocity. However, the relation of each of the neuropsychological factors to velocity remained significant even after adjusting for the effect of gait abnormality.

The standardized beta coefficients provided information with respect to the magnitude of the relation between the predictors and dependent measure. As judged by the coefficient size, the Speed/Executive Attention factor had the largest contribution to the prediction of velocity among the neuropsychological factors. The coefficients of the Memory and Verbal IQ factors were comparable to each other in magnitude.

Table 6 reveals that the Speed/Executive Attention and Memory factors were significant predictors of velocity in the interference condition, whereas Verbal IQ was not. This indicates that the

¹ The number of errors in Trails Form A was not included in the factor analysis because of a ceiling effect.

² The contribution of the cognitive factors to the prediction of gait velocity remained significant in regression models in which the demographic variables and clinical diagnosis of gait abnormality were entered in the first two blocks and the cognitive factors were entered in the third block.

Table 2

Velocity and Other Quantitative Gait Parameters of Normal Walking for the Entire Sample and as a Function of Clinical Diagnosis of Gait Abnormality

Parameter	Overall		Abnormal gait		Normal gait	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
<i>N</i>	186		73		113	
Velocity, cm/s	97.00	23.60	82.50	23.00	106.60	18.80
Cadence, step/min	102.70	11.60	98.10	11.60	105.60	10.70
Step length, cm	56.60	10.60	50.10	11.10	60.70	7.90
Stride length, cm	112.70	20.90	100.30	21.90	120.90	15.60
Stride-length CV	3.40	2.30	4.10	2.60	2.90	1.90
Double support time, s	27.20	4.50	29.30	5.40	25.80	3.10

Note. All parameters are significant at $p < .001$ level comparing normal and abnormal gait with t test for independent groups. CV = coefficient of variation.

neuropsychological factors were differentially related to velocity in the alone and the interference conditions. Among the demographic variables, only age was significantly related to velocity. As expected, gait abnormality was a significant predictor of velocity. The relation of the Speed/Executive Attention and Memory factors to velocity remained significant even after controlling for the effect of clinical diagnosis of gait abnormality. As judged by the standardized coefficient size, the Speed/Executive Attention factor had a larger contribution to the prediction of velocity compared with the Memory factor. Finally, in both regression analyses inclusion of clinical diagnosis of gait abnormality affected the relationship of gender and velocity in that it became statistically significant.

General Discussion

To our knowledge, the present study is the first to characterize the relationship between empirically derived and statistically independent cognitive factors and gait velocity in normal aging. Our findings support the first hypothesis of the study, revealing that separate cognitive functions predicted gait velocity in cognitively

normal older adults even after adjusting for the effects of demographic variables, health condition, and clinical gait abnormality. Whereas previous research limited the scope of study of cognition and gait by focusing, almost exclusively, on the role of attention in mediating gait and posture control, this study demonstrated that both general (Verbal IQ) and specific (Speed/Executive Attention, Memory) cognitive factors were related to gait velocity in aging. Indeed, our findings showed that speed and executive control processes were important but not exclusive predictors of gait. Memory and Verbal IQ were reliable predictors of velocity as well, suggesting that the cognitive correlates of gait velocity are multifaceted.

The relationship between the cognitive factors and gait velocity varied as a function of task condition, which supported the second hypothesis of the study. The Speed/Executive Attention, Memory, and Verbal IQ factors were all related to gait velocity in the alone condition. In the interference condition, the Speed/Executive Attention and Memory factors but not Verbal IQ remained significant predictors of gait velocity.

Hence, when cognitive demands increase during gait task conditions the effects of separate cognitive factors on gait velocity variance change. It is likely that gait velocity in the interference condition is more representative of walking in public, where dis-

Table 3

Results of the Principal Components Factor Analysis

Variable	Verbal IQ	Timed attention/executive	Memory
Variance (%)	25.60	22.70	12.90
Test			
Information	.817	.144	.057
Vocabulary	.799	.174	.101
BNT	.689	.232	.120
FAS	.611	.144	.437
Digit Span	.520	.268	-.014
Block Design	.402	.610	-.057
Digit Symbol	.409	.611	.337
Trails A (time)	-.042	-.824	-.211
Trails B (time)	-.188	-.828	-.201
Trails B (errors)	-.196	-.612	-.021
FCSRT: Total score	-.041	.158	.848
Category Fluency	.493	.137	.638

Note. Values in bold indicate loading coefficients above .50. BNT = Boston Naming Test; FAS = Verbal Fluency; FCSRT = Free and Cued Selective Reminding Test.

Table 4

Summary of Regression Analyses Predicting Velocity in Normal and in the Interference Conditions

Condition	R^2	$R^2\Delta$	$F\Delta$
Velocity-Alone			
Model 1	.162	.162	11.059*
Model 2	.269	.106	6.076*
Model 3	.412	.143	40.290*
Velocity-Interference			
Model 1	.154	.154	10.288*
Model 2	.204	.049	2.557*
Model 3	.336	.163	42.302*

Note. Model 1 = Three neuropsychological factors. Model 2 = Three neuropsychological factors and demographic variables. Model 3 = Three neuropsychological factors, demographic variables and clinical diagnosis of gait abnormality.

* $p < .05$.

Table 5

Regression Coefficients of the Neuropsychological Factors, Demographic Variables, and Clinical Assessment of Gait Predicting Velocity in the Alone Condition

Factor	Velocity–Alone			Velocity–Alone + Gait abnormality		
	β	<i>B</i>	<i>p</i>	β	<i>B</i>	<i>p</i>
Speed/Executive Attention	.281	6.624	.000	.194	4.576	.004
Memory	.176	4.179	.015	.160	3.778	.015
Verbal IQ	.173	4.063	.025	.166	3.919	.016
Gender	.117	5.571	.118	.149	7.044	.029
Age	–.210	–1.128	.003	–.179	–.964	.005
Education	–.186	–1.323	.014	–.164	–1.163	.016
Disease index	–.164	–3.253	.018	–.118	–2.335	.060
*Gait abnormality				.397	19.155	.000

Note. Coefficients for the neuropsychological factors are adjusted for demographic variables in Velocity–Alone and for demographic variables and clinical diagnosis of gait abnormality in Velocity–Alone + Gait Abnormality.

*Clinical diagnosis of gait abnormality was determined according to standardized published criteria and independent of the neuropsychological test scores and quantitative gait assessments.

tracting visual and verbal stimuli are continuously negotiated, than is velocity in the alone condition. This suggests that speed/executive attention and memory function are important when the individual has to walk in a busy environment.

The potency of the Speed/Executive Attention factor in predicting velocity in both the alone and the interference conditions is noteworthy. Previous research has suggested that the executive functions were better predictors of functional outcome than other neuropsychological tests (Burgess, Alderman, Evans, Emslie, & Wilson, 1998). The present study extends this association to gait performance in normal aging. The relationship between the Speed/Executive Attention factor and gait velocity in the interference condition is consistent with recent cognitive research indicating that executive control may underlie age-related dual-task effects (Holtzer et al., 2004, 2005).

The finding that the Speed/Executive Attention factor also mediated uninterrupted gait velocity provided, perhaps, even

more compelling evidence in support of the role speed and executive control processes have in gait execution. This finding is consistent with recent research (Hausdorff, Yogev, Springer, Simon & Giladi, 2005) in suggesting that, at least in old age, walking is a complex task that requires the involvement of higher order executive control processes.

However, an additional explanation concerning the relationship between the speed/executive attention processes and gait should be considered as well. The neuropsychological tests loading on the Speed/Executive Attention factor all rely on processing speed. Velocity, which was used to measure gait in the present study, is a measure of speed. Hence, it is likely that shared demands on speed of processing contributed to the relationship between gait velocity and the Speed/Executive Attention factor. Given that variability in reaction time, which is considered to be a measure of executive function, is compromised in aging (West, Murphy, Armilio, Craik & Stuss, 2002; West, 2001) these two explanations

Table 6

Regression Coefficients of the Neuropsychological Factors, Demographic Variables, and Clinical Assessment of Gait Predicting Velocity in the interference condition

Factor	Velocity–Interference			Velocity–Interference + Gait Abnormality		
	β	<i>B</i>	<i>p</i>	β	<i>B</i>	<i>p</i>
Speed/Executive Attention	.269	6.531	.001	.179	4.351	.011
Memory	.173	4.063	.024	.156	3.805	.022
Verbal IQ	.081	1.949	.315	.074	1.787	.303
Gender	.113	5.509	.153	.147	7.174	.039
Age	–.171	–.944	.022	–.138	–.761	.040
Education	–.032	–.233	.685	–.010	–.077	.881
Disease index	–.108	–2.199	.135	–.058	–1.184	.370
*Gait Abnormality				.424	21.141	.000

Note. Coefficients for the neuropsychological factors are adjusted for demographic variables in Velocity–Interference and for demographic variables and clinical assessment of gait abnormality in Velocity–Interference + Gait Abnormality.

*Clinical diagnosis of gait abnormality was determined according to standardized published criteria and independent of the neuropsychological test scores and quantitative gait assessments.

concerning the relationship between gait and timed attention/executive processes are not necessarily incompatible. Nonetheless, future research should include both “simple” and “complex” measures of speed of processing to address this issue.

The structural correlates of cortical gait control have not been well established. As reviewed earlier, poor balance and abnormal gait in aging were related to atrophy in both the temporal lobe (Guo et al., 2001) the frontal lobe (Kerber et al., 1998) and to periventricular white matter abnormality (Benson et al., 2002; Whitman et al., 2001; Whitman et al., 1999). Numerous studies provided evidence in support of the role the temporal lobes have in mediating memory and learning (Broadbent, Clark, Zola, & Squire, 2002). The involvement of the frontal lobes in executive processes, although complex (Stuss & Alexander, 2000; Stuss & Levine, 2002), has been supported by a large body of recent patient and imaging studies (D’Esposito & Postle, 2002; Curtis & D’Esposito, 2003). The relationship between white matter abnormalities and reduced speed of processing has been demonstrated in clinical populations (Dow, Seidenberg, & Hermann, 2004) and in normal aging (Gunning-Dixon & Raz, 2000). The Speed/Executive Attention factor, as discussed earlier, consisted of several timed neuropsychological tests. Hence, the relation of attention and executive processes as well as memory function to gait velocity appears to have a neural basis. Future research should examine this issue directly.

Cognitive variables share age-related variance with noncognitive variables (Salthouse & Ferrer-Caja, 2003). Hence, when evaluating age-related cognitive effects on specified outcomes, the possible confounding effects of noncognitive factors may be difficult to quantify. Whereas previous research compared dual-task performance of young and old individuals to infer the relation of attention to variance in gait performance, the current study uses a large sample of cognitively normal elders. This presents a methodological advantage in that the relation of the cognitive factors to gait performance was demonstrated without the possible confound of the general effect of aging. Moreover, controlling for the effect of potential confounders such as age, health status, and gait abnormality did not attenuate the association between cognition and gait.

Limitations

The limitations of the present study should be considered. This sample is one of convenience inasmuch as only a proportion of the participants enrolled in the EAS participated in the present study. However, our focus was on determining the relationship between cognitive processes and gait in normal aging. Our findings need be replicated in larger samples and with a wider spectrum of cognitive performance. Specifically, it is of interest to evaluate whether the general and relative contribution of the neuropsychological factors to the explained gait velocity variance can be generalized to healthy younger individuals as well as to patients with dementia. The quantitative gait evaluations were done at different study visits, though our analyses suggest that adjusting for study wave did not influence the results. Strengths of our study include the systematic clinical evaluations, quantitative gait assessments, and neuropsychological test procedures, which have been validated in our sample and elsewhere.

Future Implications

Examining the relationship between cognition and gait has significant public health implications. Abnormal gait patterns predict future risk of non-Alzheimer dementia (Verghese, Lipton, et al., 2002) and gait velocity is a sensitive proxy for the risk of falls among cognitively normal elders (Verghese, Buschke, et al., 2002). The negative consequences of falls on the elderly, which include loss of independence, institutionalization, and death have been discussed elsewhere (Cummings et al., 1995; Tinetti et al., 1994; Sattin, 1992; Tinetti, Speechly, & Ginter, 1988). Tinetti et al. (1988) identified cognitive impairment (“Relative Risk 2.3”) as one of the leading risk factors for falls in community-dwelling elderly. However, it is not known whether global cognitive declines or involvement of specific cognitive domains are responsible for falls. Verghese, Buschke, et al. (2002) showed that concomitant execution of verbal and gait tasks predicted falls in cognitively normal elders, suggesting that increased attentional demands were etiologically relevant to the risk of falls. The current study extended these previous findings by providing a detailed analysis of the cognitive processes, which underlie gait performance on the same paradigm used by Verghese, Buschke, et al. (2002). Hence, our findings suggest that individual differences in speed, executive attention, memory, and verbal IQ are important in understanding variance in gait performance in aging, which in turn is predictive of falls. This would suggest that performance on neuropsychological tests, especially those tapping speed executive control and memory demands, may provide incremental diagnostic information relevant to the risk assessment of falls in older adults. Furthermore, cognitive rehabilitation or pharmacological intervention targeting modifiable and relevant cognitive functions may reduce the probability of future falls in individuals at risk.

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