Cognitive and Motor Mechanisms Underlying Older Adults' Ability to Divide Attention While Walking

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Background. An impaired ability to allocate attention to gait during dual-task situations is a powerful predictor of falls.

Objective. The primary purpose of this study was to examine the relative contributions of participant characteristics and motor and cognitive factors to the ability to walk while performing cognitive tasks. The impact of cognitive task complexity on walking also was examined.

Design. A cross-sectional, exploratory study design was used.

Methods. Seventy-seven community-dwelling older adults with a mean (SD) age of 75.5 (5.8) years completed comprehensive testing. Participant characteristics were assessed via questionnaires. The motor test battery included measures of strength (force-generating capacity), gait speed, and static and dynamic balance. The cognitive abilities test battery assessed psychomotor and perceptual speed, recall and working memory, verbal and spatial ability, and attention (sustained, selective, and divided). Time to walk while performing 4 cognitive tasks was measured. In addition, dual-task costs (DTCs) were calculated. Multiple hierarchical regressions explored walking under dual-task conditions.

Results. The ability to walk and perform a simple cognitive task was explained by participant characteristics and motor factors alone, whereas walking and performing a complex cognitive task was explained by cognitive factors in addition to participant and motor factors. Regardless of the cognitive task, participants walked slower under dual-task conditions than under single-task conditions. Increased cognitive task complexity resulted in greater slowing of gait: gait DTCs were least for the simplest conditions and greatest for the complex conditions.

Limitations. Walking performance was characterized by a single parameter (time), whereas other spatiotemporal parameters have been related to dual-task performance. However, this type of measurement (timed performance) will be easy to implement in the clinic.

Conclusions. Two factors—participant characteristics and motor abilities—explained the majority of variance of walking under dual-task conditions; however, cognitive abilities also contributed significantly to the regression models. Rehabilitation focused on improving underlying balance and gait deficits, as well as specific cognitive impairments, may significantly improve walking under dual-task conditions.

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Interventions to improve balance ability and reduce the incidence of falls in older adults typically have focused on improving musculoskeletal impairments, integrating sensory input for balance, and promoting gait activities. However, an impaired ability to allocate attention to balance under dual-task conditions may contribute significantly to falls.[1,2] In older adults, an increased difficulty maintaining balance under divided attention conditions may result from cognitive or motor deficits.[3] Potential cognitive deficits include an inability to shift attention between 2 tasks and reduction in attentional capacity. Motor deficits of the postural control system may result in an increased demand for limited attentional resources.

Specific cognitive abilities have been correlated with walking while performing a cognitive task.[4–8] Executive functions (ie, higher-order cognitive processes that control and regulate behavior) play a prominent role in walking under divided attention conditions.[4–7] Successful mobility under dual-task conditions also has been attributed to sustained attention, selective attention to relevant stimuli, information processing speed, and memory.[6,8]

The extent to which underlying balance and gait impairments contribute to difficulty walking under divided attention conditions is not clear. Hausdorff et al[9] found that degradation of gait under dual-task conditions was attributable to executive function, dynamic balance performance, and depression. Verghese et al[2] found that fallers and nonfallers differed in gait performance under dual-task conditions, but not on screening measures of mobility or general cognitive status.

Participant characteristics such as depression, anxiety, or balance-related self-efficacy also may affect dual-task ability because of their impact on gait and mobility.[10,11] Previous studies[2,9] have been limited by a small number of motor or cognitive measures or a restricted range of balance abilities. Thus, the relative contributions of participant characteristics and motor and cognitive factors to maintaining balance under dual-task conditions remain poorly understood. The primary purpose of this study was to more closely examine the relative contributions of select participant characteristics and motor and cognitive factors to the ability to walk while performing cognitive tasks, a collective relationship that has not been fully explored.

The dual-task literature is varied and includes a number of different gait and cognitive tasks to assess "walking while thinking." In addition, findings from dual-task studies are inconsistent, with some studies demonstrating a relationship between impaired dual-task ability and falls,[2,7,12] whereas other studies have not demonstrated this relationship.[13,14] Gait tasks have included walking at preferred or fast speed, with or without a turn and with or without obstacles, with the assumption that fast speed, a turn, or obstacles present additional challenges.[15] Cognitive tasks have included verbal response to auditory or visual stimuli, sentence completion, and a variety of math and memory tasks.[3] The extent to which these different gait or cognitive tasks require additional or different cognitive resources, or

The Bottom Line

What do we already know about this topic?

Difficulty walking under dual-task situations (eg, "walking while thinking") may contribute to falls in older adults. The relative contributions of participant characteristics, motor factors, and cognitive factors to walking under dual-task conditions remain poorly understood.

What new information does this study offer?

The ability to walk while performing a simple cognitive task was explained by participant characteristics (sex and health-related quality of life) and motor factors (primarily gait speed) alone. Walking and performing complex cognitive tasks was explained by cognitive factors (eg, working memory and sustained attention) in addition to participant characteristics and motor factors.

If you're a patient, what might these findings mean for you?

Rehabilitation focused on improving underlying balance and gait deficits as well as specific cognitive impairments may significantly improve your ability to walk under dual-task conditions.

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differentially affect walking under dual-task conditions, is unclear. Thus, a secondary purpose of this study was to examine the impact of 4 different cognitive tasks of variable complexity on walking under dual-task conditions.

Method

Participants

Community-dwelling older adults from metropolitan Atlanta were recruited via flyers and presentations at local senior centers and advertisements in senior newsletters. Inclusion criteria for the study were age (≥65 years), ability to walk household distances without an assistive device, and ability to stand for at least 20 minutes. Individuals were excluded if they had cognitive impairments (>2 errors on the Short Portable Mental Status Questionnaire[16]), progressive neurological conditions (eg, Parkinson disease, multiple sclerosis), or medical conditions that would affect participation. The target sample size of 80 was based on the goal of identifying 20 participants who met criteria for difficulty walking while talking[2] for an intervention study.

Complete demographic information for the 77 community-dwelling older adults who participated are shown in Table 1. The mean (SD) age of the group was 75.5 (5.8) years, and two thirds were female. All participants gave informed consent prior to enrollment.

Table 1.
Participant Characteristics[a]

Variable	Value
Participant characteristics	
Age (y), $\overline{X}$±SD, range	75.5±5.8, 65–86
Sex, n (%)	
Female	49 (64)
Male	28 (36)
No. of comorbidities, $\overline{X}$±SD, range	3.3±1.5, 1–6
Race/ethnicity (%)	
Other	4
Black	27
White	69
Education level (%)	
High school equivalent or less	14
Some college or vocational training	39
College graduate or higher	47
No. of falls in past year, $\overline{X}$±SD, range	1.4±1.8, 0–7
ABC, $\overline{X}$±SD, range	77.7±17.7, 20.3–99.4
GDS, $\overline{X}$±SD, range	2.5±2.8, 0–12 (≥12=severe depression)
SF-12, $\overline{X}$±SD, range	
Physical component summary	41.3±11.2, 5.2–58.3
Mental component summary	51.7±11.2, 6.4–77.1
Physical factors, $\overline{X}$±SD, range	
30-s chair stand test	10.3±4.0, 0–23
SOT	64.6±12.5, 34–87
mBBS (/36)	31.7±4.3, 17–36
DGI (/24)	19.0±3.5, 8–24
Preferred gait speed (m/s)	1.01±0.24, 0.57–1.59
Cognitive factors, $\overline{X}$±SD, range	
Vocabulary (no. correct)	25.7±12.9, 1–47
Digit symbol substitution (no. correct)	42.6±11.8, 15–66
Trail Making Test, part A (s)	46.6±19.1, 15.8–107.9
Trail Making Test, part B (s)	134.2±76.2, 48.7–385.4

[a] ABC=Activities-specific Balance Confidence Scale, GDS=Geriatric Depression Scale, SF-12=12-Item Health Survey questionnaire, mBBS=modified Berg Balance Scale, SOT=Sensory Organization Test, DGI=Dynamic Gait Index.

Protocol

After telephone screening to ascertain whether prospective participants met the inclusion and exclusion criteria, questionnaires regarding demographic information, falls and health history, balance-related confidence, physical activity level, symptoms of depression, and health-related quality of life (QOL) were mailed to eligible participants and they were asked to complete the questionnaires prior to their initial visit. At the initial visit, participants were screened to exclude those with visual impairment (corrected acuity worse than 20/70) and severe hearing impairment (>70 dB threshold with hearing aids as needed). A thorough assessment of cognitive function, balance, and mobility was conducted in the Movement Studies and Balance Labs at the Atlanta Veterans Affairs Medical Center. Testing order of cognitive and physical performance measures was alternated to reduce fatigue and frustration, but was held constant across participants. Testing was administered individually, and the majority of participants completed testing in two 2-hour sessions on separate days.

Age, sex, presence of comorbidities, and fall history were assessed by questionnaire. Overall balance-related self-efficacy was determined using the Activities-specific Balance Confidence (ABC) Scale.[17] Physical activity was assessed using the Community Healthy Activities Model Program for Seniors (CHAMPS) activities questionnaire for older adults.[18] Depression was assessed using the 15-item Geriatric Depression Scale (GDS), with scores of 12 or greater indicating severe depression.[19] The Quality Metric Incorporated and Medical Outcomes Trust 12-item Health Survey questionnaire (SF-12) was used to assess health-related QOL and yields physical and mental component summary measures.[20]

Motor Test Battery

Leg strength (force-generating capacity) was determined using the standard protocol for the 30-second chair stand test.[21] The total number of sit-to-stands completed in 30 seconds was recorded. Preferred gait speed was determined using a stopwatch to time the middle 6 m of a 9-m path. Gait speed has excellent test-retest reliability (r=.90).[22] The ability to use sensory information for balance was assessed using computerized dynamic posturography (NeuroCom*). Sensory input is systematically altered during the Sensory Organization Test (SOT), and an equilibrium score is calculated for each condition. The SOT composite score, a weighted average of the 6 sensory conditions, has good validity and reliability and was the outcome measure of interest.[23] Fall risk was measured using the Dynamic Gait Index (DGI), which assesses the individual's ability to modify gait with external demands, such as changing speed, turning the head, avoiding obstacles, and stair climbing.[24] The DGI has excellent interrater and test-retest reliability (.96–.98).[24] A maximum total score of 24 points is possible, and a total score of less than 20 points is indicative of fall risk. A modified version of the Berg Balance Scale (mBBS) was used to assess balance while participants performed common daily activities such reaching, turning, and stepping.[25] By deleting the first 5 items (which are the easiest), the maximum possible score is 36 points. Sensitivity and specificity for identifying fallers is not different for the mBBS compared with the standard BBS in community-dwelling older adults; thus, to reduce administration time and fatigue, the mBBS was used.[25] The Timed "Up & Go" Test (TUG) is commonly used to assess functional mobility in older adults.[26] Time to complete the TUG was recorded.

Cognitive Abilities Test Battery

A battery of cognitive tests was administered to examine the following cognitive abilities: psychomotor speed (simple and choice reaction time tests),[27] perceptual speed (digit symbol substitution [DSS] and Trail Making Test, part A),[28,29] recall memory (DSS recall and first and last names),[28,30] working memory (Corsi blocks and alphabet span),[31,32] sustained attention (Test of Everyday Attention [TEA], elevator counting task, and TEA telephone search),[33] selective attention (TEA elevator with distraction; Stroop test; and Trail Making Test, part B),[29,33,34] divided attention (TEA telephone search plus dual-task condition),[33] verbal ability (extended vocabulary test and Controlled Oral Word Association Test [COWAT]),[30,35] and spatial ability (cube comparison).[30] These tests are widely reported in the literature, have well-established protocols, and have demonstrated reliability and validity.[36,37] Two domains—spatial ability and divided attention—consisted of a single measure. All of the other domains were represented by at least 2 measures. A brief description of each cognitive test is presented in the Appendix.

Dual-Task Battery

All gait tasks were performed at the participants' preferred speed. Participants first performed the gait tasks without a cognitive task. They performed each cognitive task while sitting before performing the cognitive task while walking. Finally, they performed the cognitive task while walking at preferred speed. Each dual-task condition was performed a single time. Two different gait tasks were used based on the Walk While Talk Test,[2] which involves a turn, and the Functional Gait Test,[38] which does not involve a turn. The Walk While Talk Test was performed with 2 different cognitive tasks: one simple (reciting the alphabet) and one more complex (reciting alternate letters). The Functional Gait Test was performed under 2 additional complex cognitive task conditions: counting backward by 3's and performing a verbal fluency task. Participants were instructed to pay equal attention to cognitive and walking tasks. The time required to walk each trial was recorded using a stopwatch. The cognitive tasks were tape recorded for further analysis.

The Walk While Talk Test was administered as published.[2] Briefly, participants were instructed to walk 6.1 m (20 ft), turn around, and walk back 6.1 m to the starting point at their preferred speed. For the simple condition (alphabet), participants walked while saying the alphabet out loud. For the complex condition (alternate letters), participants walked while saying every other letter of the alphabet out loud. For alternate letters, participants started with letter "A" in sitting,

* NeuroCom International Inc, 9570 SE Lawnfield Rd, Clackamas, OR 97015.

but started from letter "B" while walking.

The Functional Gait Test involves walking 6.1 m straight ahead at preferred speed while performing a cognitive task (counting backward by 3's or performing a verbal fluency task), while carrying a tray holding 2 cups of water, and while performing the cognitive and motor tasks at the same time.[38] In the current study, only the dual-task conditions involving cognitive tasks were examined. For the counting backward by 3's condition (count), participants started counting at a different random number for each trial. For the counting task, participants underwent three 15-second trials while sitting. There were no significant differences between the sitting trials, so the average correct response rate (CRR) is reported. For the verbal fluency condition (verbal), participants performed the same task (COWAT) as in the cognitive test battery, which occurred prior to the dual-task battery; thus, participants were already familiar with the task prior to dual-task testing. The COWAT involves naming as many words as possible, starting with a particular letter, in 1 minute. For the dual-task battery, participants performed one seated 15-second trial and 2 trials while walking (with and without carrying a tray). The 15-second seated trial was chosen because it is closer in actual time to the walking trial and during the 1-minute trials of the cognitive test battery, the response rate clearly slowed toward the end of the minute. Different letters were used for each trial.

Gait Outcome Measures

Timed performance of walking under each dual-task condition was the primary gait outcome measure. Additionally, the ratio of change in performance relative to single-task condition was calculated to quantify the change in performance under dual-task conditions (ie, dual-task costs [DTCs]). The use of performance under a single-task condition in the calculation of DTCs controls for individual differences in baseline performance. A positive value indicates worse performance under dual-task conditions (ie, longer time to walk), whereas a negative value indicates better performance under dual-task conditions (ie, shorter time to walk). Gait DTCs were calculated for each of the 4 dual-task conditions, as illustrated here for walking while reciting the alphabet:

$$\textit{Gait DTC for alphabet} = \frac{(\textit{Gait time}_{alphabet} - \textit{Gait time}_{baseline})}{\textit{Gait time}_{baseline}}$$

Cognitive Outcome Measures

To understand potential trade-offs in successfully completing the dual-task conditions, it is important to examine cognitive, as well as motor, task performance. The CRR (response rate per second × percent correct) was calculated for each of the cognitive tasks under seated and walking conditions.[39] Correct response rate accounts for both speed and accuracy of responses.

Cognitive DTCs of CRR were calculated for each of the four cognitive task conditions as illustrated below. A positive value indicates worse performance under dual-task conditions (ie, lower CRR), whereas a negative value indicates better performance under dual-task conditions (ie, higher CRR).

$$\textit{Cognitive DTC for alphabet} = \frac{(CRR_{alphabet\text{-}seated} - CRR_{alphabet\text{-}walk})}{CRR_{alphabet\text{-}seated}}$$

Data Analysis

Descriptive statistics were used to summarize the characteristics of the sample. Missing data accounted for less than 4% of timed gait data and up to 25% of cognitive data due to technical difficulties with voice recordings and were not imputed. The characteristics (age, sex, number of falls, number of comorbidities, depression, QOL, and motor and cognitive abilities) of the participants who contributed to the cognitive DTC data were not different from those who contributed to the gait DTC data; thus, the impact of missing data is believed to be minimal.

In order to examine the relative contributions of specific factors to the ability to walk while performing cognitive tasks, 8 multiple hierarchical regression analyses were performed, with timed gait performance and gait DTCs for each of the 4 dual-task conditions as the dependent variables. First, factor analysis was used to create composite ability factors from individual test scores (see "Cognitive Abilities Test Battery" section). Composite factors were chosen because they have greater reliability given multiple indicators of a construct and are an effective data reduction technique to bolster statistical power. The factor scores were used for subsequent analyses. Spatial ability and divided attention were represented by a single test, so the raw scores from these were used in the analyses. A composite dynamic balance variable was created from performance on the DGI, mBBS, and TUG. Leg strength, gait speed, and static balance (SOT) were represented by a single test, so the raw scores were used in analyses.

Prior to building regression models, diagnostic plots of residuals and influence statistics were examined to check for normality and to identify influential data points. In an effort to develop parsimonious hierarchical regression models of factors associated with timed performance as well as gait DTCs of walking while performing cognitive tasks, we first

Table 2.
Spearman Rho Correlation Coefficients and Sample Size (in Parentheses) for Gait Time (in Seconds) Under Dual-Task Conditions and Participant Characteristics, Motor Abilities, and Cognitive Abilities Without 2 Outliers[a]

Factor	WWT With Alphabet	WWT With Alternate Letters	FGT With Count	FGT With Verbal
Age	−.06 (75)	.05 (75)	−.08 (75)	.03 (73)
Physical activity	−.34† (75)	−.18 (75)	−.32† (75)	−.31† (73)
Depression	.29* (75)	.20 (75)	.22 (75)	.16 (73)
Comorbidities	.16 (72)	.00 (72)	.11 (72)	.08 (71)
Health-related QOL (physical)	−.38[b,†] (75)	−.24* (75)	−.32[b,†] (75)	−.34[b,†] (73)
Health-related QOL (mental)	−.24* (75)	−.24* (75)	−.27* (75)	.17 (73)
ABC	−.42‡ (74)	−.31† (74)	−.39† (74)	−.42‡ (72)
30-s chair stand test	−.53‡ (75)	−.35† (75)	−.43‡ (75)	−.44‡ (73)
SOT	−.35† (75)	−.36† (75)	−.40‡ (75)	−.46‡ (73)
Gait speed	−.84[b,‡] (75)	−.71[b,‡] (75)	−.84[b,‡] (75)	−.82[b,‡] (73)
Dynamic balance ability[c]	−.71‡ (75)	−.57‡ (75)	−.63‡ (75)	−.65‡ (73)
Spatial ability	−.06 (72)	−.15 (72)	−.05 (72)	−.09 (70)
Verbal ability[c]	−.33† (75)	−.24* (75)	−.31† (75)	−.35† (73)
Psychomotor speed[c]	.40‡ (75)	.35† (75)	.41[b,‡] (75)	.34† (73)
Perceptual speed[c]	−.34† (72)	−.36† (72)	−.31† (72)	−.29[b,*] (70)
Recall memory[c]	−.26* (74)	−.22 (74)	−.26* (74)	−.29* (72)
Working memory[c]	−.40[b,‡] (74)	−.41‡ (74)	−.45‡ (74)	−.37† (72)
Selective attention[c]	−.43‡ (74)	−.32† (74)	−.39† (74)	−.36† (72)
Sustained attention[c]	−.36† (73)	−.43[b,‡] (73)	−.35† (73)	−.31† (72)
Divided attention	.25* (72)	.33† (72)	.25* (72)	.22 (71)

[a] WWT=Walk While Talk Test, FGT=Functional Gait Test, QOL=quality of life, ABC=Activities-specific Balance Confidence Scale, SOT=Sensory Organization Test. *$P<.05$, †$P<.01$, ‡$P<.001$.
[b] Indicates those factors that were significant in multiple regression analyses.
[c] Indicates composite measures.

determined significant relationships among participant characteristics and motor and cognitive factors with walking under dual-task conditions using bivariate correlations (with the exception of sex, for which t tests were used to determine significance at $P<.05$). Spearman correlations were used because the data were skewed. Participant characteristics and motor and cognitive factors that were significantly correlated ($P<.05$) were entered into 8 separate linear regression models to identify which factors were most strongly associated (using correlations and beta weights) with walking performance (both timed performance and gait DTCs) under the different dual-task conditions (alphabet, count, alternate letters, and verbal). Finally, multiple hierarchical regression analyses were performed, with personal factors being entered first, motor factors second, and cognitive factors entered last to examine additional variance explained by cognitive factors.

To determine the impact of cognitive tasks of different complexity on walking, we compared change in walking performance (ie, gait DTCs) for the different cognitive tasks. Because performance can degrade in one or both of the activities performed simultaneously when they exceed the available attentional resources, it is important to examine change in both activities; thus, we also examined the cognitive DTCs. The data did not meet assumptions of normal distribution and were skewed; therefore, the nonparametric Wilcoxon signed rank test was used to determine the impact of different cognitive tasks on DTCs. Bonferroni correction was made for 6 comparisons within each variable (gait DTCs and cognitive DTCs); thus, significance level was set at $P<.008$. The data were analyzed using SPSS version 17.0.†

† SPSS Inc, 233 S Wacker Dr, Chicago, IL 60606.

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Results

With targeted recruitment, we oversampled individuals with a history of falling (57% had experienced at least one fall in the past year compared with the expected 30%), and as a whole the group was at risk for falls based on DGI scores. Even though the group was at risk for falls, participants were active in the community, with only 5 participants leaving their house fewer than 3 times per week.

Hierarchical Regression Models of Gait Performance Under Dual-Task Conditions

Diagnostic analysis identified 2 participants who were more than 3 standard deviations outside the mean gait speed and who had excessive influence (based on Cook's distance and leverage) on the analyses. The data of these 2 outliers were removed from all further regression analyses. Bivariate correlations were calculated to determine which of the personal, motor, and cognitive factors were significantly correlated with gait performance (both timed performance and gait DTCs) while performing each cognitive task (Tab. 2). The participant characteristics that were most correlated to gait time under dual-task conditions were physical activity, physical health-related QOL, and balance-related self-efficacy. There were significant sex differences for gait time under dual-task conditions of alphabet, count, and verbal. All of the motor factors were correlated to gait time under each dual-task condition. The majority of cognitive factors were correlated to gait time under dual-task conditions, with the exception of spatial ability. Of the participant characteristics, gait DTCs for count were significantly different for sex, and age was significantly correlated to gait DTCs for verbal. Only divided attention was significantly correlated with gait DTCs for alphabet. Factors (personal characteristics, motor, and cognitive) identified through bivariate correlation (or *t* tests for sex) then were subjected to separate regression analyses, and significant factors entered into hierarchical regressions are indicated in Table 2.

Table 3.
Predictive Regression Models of Timed Gait Performance Under Dual-Task Conditions Without 2 Outliers[a]

Cognitive Task	Variable	ΔR^2	Standardized β^b	P^b
Alphabet (n=74)	Participant characteristics	.322		
	Health-related QOL (physical)		−.217	.005
	Sex		−.079	.276
	Motor	.339		
	Gait speed		−.633	<.001
	Cognitive	.010		
	Psychomotor speed		.110	.143
Alternate letters (n=74)	Motor	.397		
	Gait speed		−.555	<.001
	Cognitive	.053		
	Sustained attention		.243	.011
Count (n=74)	Participant characteristics	.306		
	Sex		−.157	.033
	Health-related QOL (physical)		−.173	.024
	Motor	.358		
	Gait speed		−.616	<.001
	Cognitive	.018		
	Working memory		.150	.050
Verbal (n=72)	Participant characteristics	.250		
	Sex		−.075	.369
	Health-related QOL (physical)		−.125	.146
	Motor	.345		
	Gait speed		−.642	<.001
	Cognitive	.010		
	Working memory		−.111	.193

[a] Only significant variables are reported. QOL=quality of life.
[b] Reported values are for the final model.

The results of the hierarchical regression analyses for timed gait performance are presented in Table 3. The associated factors were as follows:

- Walking and reciting the alphabet: SF-12 (physical component) and preferred gait speed.
- Walking and reciting alternate letters: preferred gait speed and sustained attention.
- Walking and counting: sex, SF-12 (physical component), preferred gait speed, and working memory.
- Walking and verbal fluency: preferred gait speed.

Table 4.
Mean (SD) of Gait and Cognitive Dual-Task Costs for Each Condition[a]

Variable	WWT With Alphabet	WWT With Alternate Letters	FGT With Count	FGT With Verbal
Gait DTCs (%)	4 (12) n=76	29 (34)[b,c] n=76	18 (24)[b] n=77	30 (33)[b,c] n=75
Cognitive DTCs (%)	17 (20) n=63	4 (30)[b,c] n=61	−24 (46)[b] n=61	−44 (58)[b,d] n=58

[a] Wilcoxon signed rank tests were used to examine differences among conditions. The ratio values have been multiplied by 100 to convert to a percentage for ease in interpretation. A positive value indicates percentage of decrement in performance from single-task condition; a negative value indicates percentage of improvement in performance from single-task condition. WWT=Walk While Talk Test, FGT=Functional Gait Test, DTCs=dual-task costs.
[b] Significantly different ($P<.008$) from alphabet.
[c] Significantly different ($P<.008$) from count.
[d] Significantly different ($P<.008$) from alternate letters.

Gait DTCs for alphabet were associated only with divided attention ($r=.264$, $P=.026$), and gait DTCs for verbal were associated only with age ($r=.289$, $P=.013$).

Gait Performance Under Dual-Task Conditions

Regardless of the specific cognitive task, participants walked slower (ie, took longer and DTCs, therefore, were positive) under dual-task conditions than under single-task conditions (Tab. 4). Wilcoxon signed rank tests revealed that gait DTCs were significantly lower for alphabet compared with all other conditions ($P<.001$). Gait DTCs were significantly lower for count compared with alternate letters and verbal ($P\leq.001$). Gait DTCs for alternate letters and verbal did not differ ($P=.74$). Outlier analysis revealed 3 outliers. Removing outliers, however, did not alter the findings; thus, reported values include outliers.

Cognitive Performance Under Dual-Task Conditions

Participants performed the alphabet and alternate letters tasks more slowly while walking compared with sitting down (positive cognitive DTCs). To the contrary, participants performed the counting and verbal fluency tasks more quickly while walking compared with sitting down (negative cognitive DTCs; Tab. 4). Wilcoxon signed rank tests revealed that cognitive DTCs for alphabet was significantly higher than alternate letters, count, and verbal ($P\leq.002$). Cognitive DTCs for alternate letters was significantly higher than for count and verbal ($P<.001$). Cognitive DTCs for count and verbal were not different ($P=.10$). Outlier analysis revealed 2 outliers. Removing outliers did not change the findings; thus, reported values include outliers.

Discussion

For community-dwelling older adults, the ability to walk under dual-task conditions is a powerful predictor of falls[2]; thus, understanding the mechanisms underlying dual-task ability is important for developing appropriate interventions. In the current study, even the simplest cognitive task performed while walking resulted in a slower gait, which became even slower with increasing cognitive task complexity. The ability to walk while performing a simple cognitive task (reciting the alphabet) could be explained by participant characteristics and motor factors alone, whereas walking and performing more-complex cognitive tasks were explained by cognitive factors in addition to participant characteristics and motor factors. Specifically, working memory and sustained attention explained performance of walking while reciting alternate letters and counting backward by 3's.

Relative Contribution of Personal, Motor, and Cognitive Factors to Dual-Task Ability

The results of this study indicate that the motor factor, preferred gait speed, explained a greater proportion of variance in timed walking under dual-task conditions. Preferred gait speed alone accounted for approximately one third of the variance. Participant characteristics, primarily physical health-related QOL and sex, accounted for an additional 25% to 32% of the variance. These 2 factors—participant characteristics and motor abilities—alone explained a significant proportion of the variance. However, with increased complexity of the cognitive task, underlying cognitive abilities also contributed significantly to the model.

Because gait speed is such a critical factor in walking while thinking, rehabilitation that is focused on improving gait impairments may be beneficial to the ability to walk under dual-task conditions. One retrospective study has demonstrated that for individuals with impaired balance and gait, physical therapy that improved gait speed also improved walking under dual-task conditions.[40] Furthermore, cognitive training, by addressing the underlying cognitive impairments, may provide additional benefits and enhance walking under dual-task conditions.

Of the 9 different cognitive abilities assessed, the majority (with the exception of spatial ability and recall memory) were significantly correlated to walking while performing a cognitive task. However, in hierarchical regression analyses, only working memory, sustained attention, and divided attention were significantly related to walking while performing cognitive tasks. No other study has included such a broad array of cognitive measures in conjunction with physical performance measures. Importantly, this study is the first to include a measure of divided attention: the ability to simultaneously perform 2 tasks. Divided attention was strongly associated with gait DTCs while reciting the alphabet.

Our results support a consistent finding in previous research that general cognitive ability, spatial ability, and recall memory are not critical to dual-task ability.[41] In addition, this study provides converging evidence that aspects of executive function (eg, sustained attention) are important to dual-task ability, akin to previous findings in which successful obstacle avoidance under dual-task conditions was predicted by executive function (eg, both selective and sustained attention), but not recall memory or spatial discrimination.[6]

In the current study, timed performance of walking under dual-task conditions was explained by personal and motor factors, but cognitive variables also contributed significantly. Two outliers were removed from regression analyses because of their excessive influence on the analyses: both participants had extremely poor cognitive abilities, which resulted in the cognitive variables explaining a much greater proportion of the variance of walking under dual-task conditions in regression analyses. Both outliers had poor walking performance under dual-task conditions; one outlier had poor divided attention ability, and the other had slow perceptual speed. Further study is warranted to investigate whether poor cognitive ability (ie, poor divided attention and slow perceptual speed) explains poor walking performance under dual-task conditions. The participants' sex was a significant factor only for timed performance of walking while counting backward by 3's. Under this condition, gait slowed by 10% for men and 22% for women. The specific role that sex played in this finding is not clear and may be elucidated in future studies.

Gait DTCs were explained by age and divided attention alone. This finding is in sharp contrast to the study by Hausdorff and colleagues,[9] who found that gait speed (the equivalent of our measure of timed performance) DTCs were explained by motor factors alone, specifically preferred gait speed or ability to perform activities of daily living. Differences in outcomes may relate to differences between samples. Our sample was of similar age, but had more-impaired gait and balance, as evidenced by a greater proportion with a history of falls, slower walking speed, and greater fall risk. In both studies, much of the variance in DTCs was unexplained.

Effect of Different Cognitive Tasks

This study assessed the effect of different cognitive conditions on walking speed in a sample of community-dwelling older adults. The 2 tasks that had the greatest impact on gait performance were reciting alternate letters and verbal fluency (30% slowing of gait). Counting backward by 3's had a modest effect (18% slowing), and reciting the alphabet had minimal impact (4% slowing). Although many cognitive tasks have been used across studies, few studies have directly compared different cognitive tasks, and those that have compared different cognitive tasks have demonstrated contradictory findings. We cannot directly compare findings because of widely divergent cognitive tasks (eg, auditory tasks, counting backward by 7's, working memory, and spontaneous speech); however, our findings and those of other authors[7,42,43] support the notion that the more complex the cognitive task, the greater the impact on gait performance in community-dwelling older adults.

A relevant question for clinicians is which cognitive task to use when assessing dual-task ability. Undoubtedly, the answer will depend on the cognitive and motor status of the individual. In the current study involving community-dwelling older adults without cognitive impairment, the simplest task (alphabet) had minimal impact on gait and thus may not be challenging enough to reveal impairments. The more-complex tasks of reciting alternate letters, counting backward, and performing a verbal fluency task significantly affected walking and thus may be relevant assessments of dual-task ability. Much remains to be learned about the effect of performing cognitive tasks of varying complexity on gait in older adults with balance or cognitive impairments.

Task Prioritization: Gait Versus Cognitive Tasks

Shumway-Cook and Woollacott[44] proposed a posture-first hierarchy of task prioritization. The results of our study did not support that hypothesis. Although participants were explicitly told to pay equal attention to walking and cognitive tasks, they slowed their walking, whereas performance improved for 2 of the 4 cognitive tasks. This pattern implies prioritization of the cognitive task for those 2 conditions.

There may be several factors contributing to prioritization of the cognitive task. Older adults can flexibly allocate attention to either gait or cognitive task performance.[45,46] Despite the instructions, participants may have prioritized the cognitive task in order not to make errors. Alternatively, some cognitive tasks are more rhythmic, and the combination of rhythmic tasks (ie, walking and counting) may result in entrainment of the tasks such that the cognitive task is performed more quickly while gait is performed more slowly.[47] In the current study, there were no consequences for slowing down in terms of gait stability, and the participants may have been unaware that they had made a trade-off between gait and cognitive task performance. If there had been consequences to slowing down (eg, having to repeat a trial, bumping an obstacle), participants might have allocated more attentional resources to gait at the cost of cognitive task performance; however, the experimental design did not allow exploration of this hypothesis.

The current findings of improved cognitive performance while walking are in contrast to previous findings. Of the few studies that examined changes in the cognitive task under dual-task conditions, most demonstrated degradation in performance of cognitive tasks (serial 3's or 7's, phoneme monitoring, and verbal fluency), with only the simplest cognitive tasks such as counting backward or answering content questions demonstrating improvement while walking.[47–49] One difficulty in comparing studies is that in the current study, a single cognitive performance variable encompassing speed and accuracy (ie, CRR) was analyzed, whereas other studies typically reported accuracy and speed of response separately, which does not allow for sorting out speed-accuracy trade-offs.

Limitations

Walking performance was characterized by a single parameter: time. Other studies have included other spatiotemporal parameters and found them to be differentially related to dual-task performance. For example, DTCs in gait speed were related to preferred gait speed, whereas DTCs in swing time variability were related to executive function, mobility, and depression.[9] However, clinicians should find this type of measurement (timed performance) easy to implement in the clinic.

It is conceivable that the research design may have contributed to the finding of improved cognitive performance while walking because the cognitive task always was performed first while sitting. Evidence for a practice effect, however, is limited because participants had already performed the verbal fluency task as part of the cognitive test battery and then performed a seated trial followed by a walking trial. Additionally, there were no differences in CRR among the 3 seated practice trials of counting backward by 3's, suggesting a lack of practice effect.

Summary and Conclusions

Gait is an attention-demanding task, and any concurrent cognitive task, even a very simple one, disrupted walking performance in community-dwelling older adults. An increase in cognitive task complexity resulted in an even greater degradation of gait. Although personal and motor factors explained the majority of variance of walking under dual-task conditions, cognitive factors also contributed significantly to the regression model. Understanding the factors associated with DTCs will provide guidance for identifying individuals at risk for falls and for developing novel interventions to improve dual-task ability.

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Appendix.

Brief Description of Cognitive Ability Tests

Cognitive Ability	Description
Psychomotor speed	*Simple reaction time*: Participants responded as quickly as possible to a visual stimulus on the computer monitor. Random foreperiods of 500, 800, 1,100, 1,400, and 1,700 milliseconds and variable intertrial intervals (1,000 and 2,000 milliseconds) were used. *Choice reaction time*: Participants responded to a visual stimulus on the computer monitor, which appeared either on the left or right of the monitor, with the corresponding right or left hand. There were 10 practice trials and a total of 60 trials for each test.
Perceptual speed	*Digit symbol substitution (DSS)*: Participants were presented with a digit-symbol key (eg, 1=X), followed by 100 digits for which they had to fill in the appropriate symbol. Score was the total number correct in 90 seconds. *Trail Making Test, part A*: Participants were presented with a series of circles labeled numerically and required to trace the sequential pattern of numbers as quickly as possible. Time to completion was recorded.
Recall memory	*DSS recall*: Participants were asked to recall the digit-symbol pairs after completing DSS test. Score was the total number correct pairs recalled. *First/last names*: Participants studied 15 full names—first and last—for 3 minutes. Then participants were shown a list of the last names in a different order and required to write the first names that go with each last name in 2 minutes. Score was the total number of correct names matched.
Working memory	*Alphabet span*: Two to nine words were presented orally (3 trials were presented at each level). The task was to recall the words in alphabetical order. Absolute span score was the total number of words recalled for trials that were recalled perfectly. *Spatial span*: Two to nine blocks were touched in a particular order, and the participants were required to point to the same blocks in reverse order. Spatial span score was the total number of correct trials.
Sustained attention	*Elevator counting test*: Participants counted strings of tones presented via CD. They were asked to imagine being in an elevator in which the visual floor indicator light is broken. As the elevator passes each floor, a tone sounds at an irregular tempo. Participants identify the floor by counting the tones. There were 2 practice trials and 7 actual trials. Score was the number of correctly counted strings. *Telephone search test*: Participants searched a telephone directory page for certain symbols as quickly and as accurately as possible. When 2 of any of the symbols were together in one line, they were asked to circle the symbols. Score was time per target.
Selective attention	*Stroop test*: Participants were given 45 seconds to complete each of 3 parts. Participants read the words presented in part 1 and the colors presented in part 2. Part 3 required participants to say the color of the ink in which the words were presented rather than the word itself (eg, the word "blue" was presented in green ink). Time to completion was measured for each of the 3 parts, and the interference score was calculated. *Trail Making Test, part B*: Participants drew a line to connect alternating numbered and lettered circles in order. Time to complete task was recorded. *Elevator counting with distraction test*: Participants counted the same tone as they heard in the elevator counting task, while not counting a distractor tone, which was a higher pitch. Score was the number of correctly counted strings.
Divided attention	*Telephone plus dual-task test*: Participants searched a telephone directory page for symbols without distractors and while counting strings of tones presented via CD. Participants were told to work as quickly and accurately as possible, putting equal effort into each of the 2 simultaneous tasks. A dual-task decrement measure was calculated by combining the scores for the telephone directory task with and without distractors.
Verbal ability	*Extended vocabulary test*: Participants were instructed to choose the synonym for each of the words given, from 4 available choices. Score was the total number correct from 48 items. *Verbal fluency*: Was assessed using the controlled oral word association test, which consisted of three 1-minute trials with a different letter. Participants were instructed to say as quickly as possible all the words that began with a particular letter, with the exception of proper names, such as names of people or places. Score was the total number of correct words for the 3 trials.
Spatial ability	*Cube comparison test*: Participants completed two 21-item parts, each with a 3-minute time limit. For each item, participants determined whether two 6-sided cubes could be the same if they were spatially manipulated by the turning each cube in a specified manner. Score was the total number correct.