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Contributions of cognitive function to straight- and curved-path walking in older adults

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Abstract

Objective—To determine whether the cognitive function contribution to straight- and curved-path walking differs for older adults.

Design—Cross-sectional observational study.

Setting—Ambulatory clinical research training center.

Participants—One hundred six people aged 65 years to 92 years, able to walk household distances independently with or without an assistive device, and who scored ≥ 24 on the Mini-Mental State Examination.

Intervention—Not applicable.

Main Outcome Measurements—Cognitive function was assessed using the Digit Symbol Substitution Test (DSST) as a measure of psychomotor speed, and Trail Making Tests A and B (Trails A, Trails B), and the Trail Making Test difference score (Trails B-A) as executive function measures of complex visual scanning and set-shifting. Gait speed recorded over an instrumented walkway was used as the measure of straight-path walking. Curved-path walking was assessed using the Figure-of-8 Walk Test (F8W) and recorded as the total time and number of steps for completion.

Results—Both DSST and Trails A independently contributed to usual gait speed ($P < 0.001$). Trails A performance contributed to F8W time ($P < 0.001$). Neither Trails B nor Trails B-A contributed to usual gait speed or time to complete the F8W. For the number of steps taken to complete the F8W, Trails A, Trails B, and Trails B-A (all $P < 0.001$) were independent contributors while DSST performance was not.

Conclusion—Curved-path walking, as measured by F8W test, involves different cognitive processes compared to straight-path walking. Cognitive flexibility and set-shifting processes uniquely contributed to how individuals navigated curved-paths. The measure of curved-path

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walking provides different and meaningful information about daily life walking ability than usual gait speed alone.

Keywords

gait; elderly; trail making test; executive function

There is considerable evidence that cognitive function is critical to the regulation of gait and balance in older adults.¹⁻⁴ Slower usual gait speed during straight-path walking has been associated both with a slowing in psychomotor speed^{5,6} and with poorer executive function.⁷⁻⁹ Executive function describes a set of high-level cognitive domains (e.g. cognitive flexibility, inhibition control, problem-solving, planning) that are necessary to plan, initiate, execute and monitor goal-directed behavior through regulation of basic cognitive abilities and attentional resources.^{10,11} Psychomotor speed is the rate at which information can be processed. It can be viewed as a general-purpose resource in that the rate of information processing limits the performance of higher-level operations such as executive abilities. There is considerable disagreement in the aging literature about the degree to which the decline in executive functioning seen with increasing age is independent of a psychomotor slowing. One view¹² is that any performance changes attributed to an age-related decline in executive functioning simply reflect a slowing in the rate at which individuals can process information and make decisions. However, there are studies¹³ showing that variance in executive performance is at least partially independent of psychomotor slowing reflecting higher-order cognitive skills. Therefore, in examining the role that cognition plays in walking it is important to use tasks that examine basic psychomotor speed as well as executive operations.

Just as a single test cannot measure all components of cognitive function, gait performance under straight-path, low challenge conditions may not correlate to the ability to walk in complex home and community environments. Walking during daily life requires us to continually adapt our walking patterns to avoid or negotiate obstacles, carry loads, change directions or plan a path.¹⁴ Currently, there is limited research examining the relationship between cognitive function and complex walking tasks in older adults. While measures of cognitive flexibility and set shifting have been associated with walking speed during negotiation of an obstacle course, these measures were not associated with usual walking speed.¹⁵ Similarly, older adults in the highest and lowest tertiles of executive function exhibited differences in gait speed during some complex walking tasks (over obstacles, picking up an object) but not during others (carrying a package, talking when walking).⁷ Together these findings suggest that the association between executive function and gait performance is task dependent.

Daily life walking also frequently involves curved-paths (eg, walking around furniture, through a grocery store, negotiating street corners). Compared to straight-path walking, curved-path walking involves different motor control processes,^{16,17} and likely different cognitive processes such as planning and navigation.^{18,19} Performance on the Figure-of-8 Walk test (F8W), a measure of curved-path walking ability, was associated with slower usual gait speeds, lower confidence in walking, and poorer physical and executive function in

older adults with mobility disability.²⁰ Whether cognitive abilities related to planning and navigation differentially contribute to curved- compared to straight-path walking is not known.

The purpose of this research was to determine if the cognitive contribution to straight- and curved-path walking is different. We examined psychomotor processing speed (DSST), executive function measures of complex visual scanning and cognitive flexibility (Trail Making Test A and B), and straight- and curved-path walking performance in a sample of community-dwelling older adults. We expected that the specific contributions of different cognitive domains would vary as a function of the gait task. We expected that psychomotor speed would contribute to straight-path walking ability, while cognitive flexibility would contribute to curved-path walking ability.

METHODS

We used baseline data collected as part of a longitudinal observational study of mobility and physical function among community dwelling older adults for this cross-sectional study of the relations between gait and cognitive function. Baseline sessions were conducted by four research physical therapists who were trained in the administration of all measures, with a manual of operations that included written scripts to ensure standardization of participant instructions for all tasks. All cognitive testing was completed in the same area using a standard card table and office lighting, free from distractions of other personnel or participants.

Participants

Participants (n = 115) were recruited from the University of Pittsburgh Pepper Center Research Registry of older adults. Individuals who were 65 years and older, able to walk household distances independently with or without an assistive device, and who scored 24 on the MMSE were included in the study. Individuals with neuromuscular disorders, cancer with active treatment, severe cardiopulmonary disease, or who had recent major illness or surgery were excluded. Baseline cognitive data were missing on nine subjects; thus, 106 subjects were included in the analyses. This study was approved by the Institutional Review Board at the University of Pittsburgh and all subjects provided written informed consent prior to participation in the study.

Gait Measures

Straight-path walking—Usual gait speed during level, unobstructed walking was used as the measure of straight-path walking. Participants walked at a self-selected comfortable speed on the GaitMatII™, a 4-m instrumented walkway, with 2-m non-instrumented sections at either end to allow for acceleration and deceleration. After 2 practice walks, each participant completed 4 walks at their usual speed, and gait speed was averaged over the 4 walks.

Curved-path walking—The Figure-of-8 Walk Test (F8W) was used as the measure of curved-path walking. Full procedures for the F8W were previously described.²⁰ Briefly,

participants started standing midway between 2 cones placed 5 feet apart and walked a figure-of-8 path around the cones. The total time (F8W time) and number of steps taken (F8W steps) to complete the course were recorded. Faster times and fewer steps indicate better curved-path walking ability. The F8W has demonstrated interrater and test-retest reliability (interrater ICCs of .90 and .92, test-retest ICCs of .84 and .82, for time and number of steps, respectively). Construct validity has been previously demonstrated by associations with physical function in daily life, activity restriction, and performance of activities of daily living.²⁰

Cognitive Measures

Digit Symbol Substitution Test (DSST)—The DSST is a well-known paper and pencil task from the WAIS-III that is largely a measure of psychomotor speed, as well as selective attention, incidental memory, and visuomotor coordination.²¹ The test consists of a key grid of numbers with corresponding symbols, followed by a test section with rows of numbers with empty spaces below them. Participants fill in as many corresponding symbols as possible in 90 seconds. The number of correct number-symbol matches was recorded, with higher scores indicating better performance

Trail Making Test A & B (Trails A, Trails B, Trails B-A)—The Trail Making Test is a widely used test of executive function that involves multiple cognitive domains²² and is administered in two parts. Completion of Trails A involves complex visual scanning, motor speed and agility^{23,24} as participants draw lines to connect consecutively numbered circles as quickly as possible. Completion of Trails B requires the additional processes of cognitive flexibility and set-shifting^{10,25} as participants connect circles in an alternating sequence of numbers and letters, linking them in ascending order as fast as possible (1-A-2-B-3-C, etc.) Trails A was administered first, immediately followed by administration of Trails B. Time to complete and number of errors for each portion were recorded. Errors were pointed out by the examiner and corrected by the participant, so that time for correction of errors was included in the total time. If Trails B was not completed in 5 minutes the test was stopped and a maximum score of 300s was recorded. Lower scores (faster times) on both parts indicate better performance. Additionally, we used a difference score (Trails B-A) calculated by subtracting Trails A from Trails B. The Trails B-A score is used to adjust the test time by the common motor speed element, resulting in a more accurate measure of the complex processes of cognitive flexibility and set-shifting unique to Trails B.^{10,26}

Data Analyses

Descriptive data are reported for all variables. The F8W data was missing for one participant, thus all the analyses involving F8W are for n=105, all other analyses n=106. Associations between variables were determined using the appropriate Pearson or Spearman Rank Order correlation coefficient. To assess the differential contributions of cognitive function to straight- and curved-path walking, a series of multiple regressions analyses were used with the measures of straight-path walking (usual gait speed) and curved-path walking (F8W time to complete and number of steps) as the dependent variables. In Model 1, we accounted for the variance in straight- and curved-path walking explained by age, gender, and processing speed (DSST). In Model 2, Trails A, Trails B and Trails B-A were

individually added to determine the additional variance in straight-and curved-path walking explained by the Trail Making executive function measures.

RESULTS

Participant Characteristics

The mean age was 77.4 years (SD 5.9), 70% were women (Table 1). Mean cognitive function scores are consistent with previously reported age-normative values for these tests.²⁷ Mean usual gait speed was 1.10 m/s for the older adults studied. This gait speed is slower than the mean usual gait speed of 1.2-1.3 m/s for adults in good health (20-79 years),²⁸ but comparable to walking speeds reported for community-dwelling older adults.²⁹ Mean F8W time and steps are slightly less (better) than those reported by Hess et al.,²⁰ who studied a group of older adults of similar age (mean 76.8 years, SD 5.5), but with known mobility limitations.

Relationships among Age, Cognitive Function, and Straight- and Curved-path Walking

In general, better psychomotor speed and executive function was associated with better (faster) usual gait speeds, and less time and fewer steps to complete the F8W (Table 2). Cognitive measures were all associated with usual gait speed and the F8W variables, with the exceptions that DSST was not associated with F8W number of steps, and Trails B-A was not associated with F8W time to complete. Measures of straight- and curved-path walking were highly related (Table 2).

Contributions of Cognitive Function to Straight- and Curved-path walking

For straight-path walking (Table 3 left column), both DSST and Trails A independently contributed to usual gait speed (Model 2 adjusted $R^2 = .22$, $P_{\text{model}} < 0.001$). Adding Trails A to the model explained an additional 4.4% of the variance in straight-path walking ($p = .017$), and reduced the contribution of DSST from 6.8% to 4.0% of the variance explained. Neither Trails B nor Trails B-A scores contributed to usual gait speed after adjusting for age, gender and DSST scores.

Different patterns of results were found for the two measures of curved-path walking ability. Trails A performance contributed to the variance explained in the time to complete the curved-path (Model 2 adjusted $R^2 = .23$, $P_{\text{model}} < 0.001$; change of 5.4%, $p = .008$). As with straight-path walking, neither Trails B nor Trails B-A contributed to time to complete the curved path (Table 3 middle column). For the number of steps taken to complete the curved-path, Trails A (Model 2 adjusted $R^2 = .20$, $P_{\text{model}} < 0.001$; change of 5.9%, $p = .007$), Trails B (Model 2 adjusted $R^2 = .22$, $P_{\text{model}} < 0.001$; change of 7.7%, $p = .002$), and Trails B-A (Model 2 adjusted $R^2 = .19$, $P_{\text{model}} < 0.001$; change of 4.4%, $p = .019$) were all contributors while DSST performance was not (Table 3, right column).

DISCUSSION

We examined whether the cognitive demands of gait differed according to the type of walking task. We found that measures of psychomotor speed and complex visual scanning

(DSST and Trails A) both contributed to straight-path walking, whereas measures of complex visual scanning and set-shifting ability contributed to curved-path walking (Trails A, B, and B-A).

Consistent with previous literature,^{5,6} DSST performance was related to straight-path walking, i.e. poorer DSST scores were associated with slower walking speeds. As the DSST is largely a measure of general processing speed and straight-path walking ability was represented by usual gait speed, the shared demands of the cognitive and gait functions on speed of processing may partially account for the relationship. Completion of the DSST also requires visuomotor coordination. Older adults are known to be more visually dependent than young adults during upright activities and visually sample the environment more often during walking than young adults³⁰. Thus, visual processes are likely relied upon even in straight-path walking tasks, and may, in addition to shared demands on processing speed, explain the contributions of DSST to straight-path walking.

A new finding from this study is that Trails A performance contributed to straight-path walking after accounting for DSST performance. Trails A, while a measure of motor performance speed, relies heavily on visual scanning processes for completion. The unique visual scanning component of Trails A performance may explain its independent contribution to straight-path walking beyond the variance explained by the DSST score. While completion of both the DSST and Trails A measures may involve visuomotor and visual scanning abilities, the measures differ in the intent or how the visual information gained is used. For DSST, visual scanning is used to locate a number or code and visuomotor abilities are then used to guide the pen to the correct box and transcribe the code onto paper. Similarly, visual scanning in Trails A performance is used to find the desired number, but in addition, visual scanning is also necessary for the individual to plan a path and negotiate the path in a continuous line from the current number location to the next number target. The visual scanning in support of path planning and navigation represented by Trails A may be uniquely different than the visual processes involved in DSST performance. The independent contribution of both measures to straight path walking illustrates the reliance of the older adults studied on visual scanning of the walking surface, even in unobstructed walking on level terrain.

In contrast to straight-path walking, the F8W test has both straight and curved sections and involves steering the body in clockwise and counter-clockwise directions. Unlike a traditional dual-task paradigm, in the F8W the cognitive demand is embedded in the task. Navigation in complex environments requires the integration of multiple sensory inputs with the planning of a goal-directed action,³¹ i.e. changing the direction of the body to navigate the curve. Prior findings have indicated that curved-path walking requires planning and specific cognitive-to-motor transformations.¹⁶ Curved- path walking also imposes greater demands on balance control compared to straight-path walking, particularly in the mediolateral direction.³² Healthy adults use trunk roll motion and adjustments in stance width and stride length of both the inner and outer legs to move the center of mass and reorient the body around the curve.^{16,33} Thus, the motor patterns for straight- and curved-path walking are different; straight-path walking is characterized by symmetry of foot placement, whereas curved-path walking is characterized by a necessary asymmetry of foot

placement. The different cognitive and motor demands of curved-path walking are reflected in our finding that the cognitive function contribution to curve-path walking was different than for straight-path walking.

The F8W time and number of steps to complete measures of curved-path walking ability revealed different patterns of associations with executive function. Time to complete the F8W was related to Trails A, and likely represents the shared demands of the curved-path gait task and the Trails A executive function task on speed and visual control. Vision may be even more important in curved-path walking, explaining the slightly greater strength of associations (greater Pearson r and standardized β) between Trails A and the time to complete the F8W compared to the associations with straight-path walking. Neither Trails B nor Trails B-A contributed to time to complete the F8W. This finding is in contrast to previous work where Trails B-A performance was associated with walking speed on an obstacle course.¹⁵ One explanation is that in the previous study participants were asked to walk the obstacle course as fast as possible, whereas in our study participants walked the curved-path at their usual pace. This speed component may have resulted in greater attention and motor planning demands, explaining their finding of an association between Trails B-A and obstacle gait speed.

In contrast to the F8W time, the number of steps taken to complete the F8W provides insight into *how* older adults accomplished the gait task. We found that Trails A, Trails B, and the Trails B-A all contributed to the number of steps taken to complete the F8W, whereas DSST performance did not. Thus, Trails B and Trails B-A uniquely contributed to how individuals navigated the curved-paths. Trails B and Trails B-A reflect processes of cognitive flexibility and set-shifting, i.e. alternating between cognitive categories. We suggest these cognitive processes underlie (are important to) the ability to switch between motor patterns, i.e. shifting from straight to curved sections, necessary to effectively complete the F8W test. Imaging studies have shown greater activations in dorsolateral prefrontal cortex for Trails B, an area known to be critically involved in rapid action and cognitive shifts.³⁴ Activation levels of the dorsolateral prefrontal cortex have been proposed as sensitive indices in evaluation of the brain function of older adults.^{35,36} Thus, a simple mobility test such as the F8W that is able to tap into these processes may be very useful in detecting early functional decline, or determining mobility ability necessary for daily living. The findings also illustrate the specific cognitive demands of different everyday gait tasks, and the intervention challenge to address the integrated gait and cognitive function required for everyday walking.

Yamada et al.³⁷ developed an ambulatory version of the Trail Making Test where subjects are asked to walk to fifteen sequentially numbered flags placed randomly in a room. Like the F8W test, this trail-walking test involved straight paths and turning. They found that the time to complete the trail-walk was better than the TUG, functional reach and one-leg standing tests in predicting falls. The F8W test has several advantages over the trail-walking test. It requires minimal equipment and set-up, is quickly administered, and can be easily and safely conducted in home settings.

Study Limitations

The limitations of the study are primarily related to sample selection. We studied well-functioning older adults specifically screened for general cognitive impairment, which restricts the ability to generalize these findings to a general population of older adults. Additionally, while the correlation and regression analyses indicate different relations between cognitive function and straight- and curved-path walking, the mechanism of the variance in associations is not clear. For example, it is not known if poorer executive function is a cause of poorer curved-path walking ability, or if the relation of curved path walking and the executive function studied is indirect through the relation of both to a common brain function. Neuroimaging correlates of curved path walking compared to straight path walking are necessary to begin to examine the basis for the gait and cognitive relations described. While differences in the relations of straight and curved path walking to physical and cognitive functions have been demonstrated, more work is needed to substantiate the clinical utility of the measure of curved path walking in diagnosis and prognosis (e.g. identifying older adults at-risk for falls or recognizing who is most likely to decline in mobility over time).

CONCLUSIONS

In summary, curved-path walking, as measured by F8W test, involves different cognitive processes compared to straight-path walking. Cognitive flexibility and set-shifting processes uniquely contributed to how individuals navigated curved-paths. These findings indicate that curved-path walking provides different and meaningful information about daily life walking ability than usual gait speed alone. While additional research is warranted to examine responsiveness of the measure and its ability to predict falls, the specific associations of curved-path walking ability and executive function suggest that the F8W test may be a very useful tool in detecting early mobility disability.

Abbreviations

F8W	figure-of-8 walk test
DSST	digit symbol substitution test
Trails A	trail making test part A
Trails B	trail making test part B

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Table 1

Characteristics of Participants (N= 106)

Variable	Mean $\pm$ 3D	Range
Age (y)	77 $\pm$ 5.8	65 to 92
Education: 12y (n [%])	79 (75)	NA
MMSE	23.3 $\pm$ 1.62	24 to 30
DSST (No. correct)	48 $\pm$ 9.8	26 to 74
TMT-A (s)	43.8 $\pm$ 13.2	16.8 to 102.3
TMT-B (s)	105.5 $\pm$ 47.4	33.3 to 300
TMT-B-A (s)	61.8 $\pm$ 45.2	-.95 to 237.36
Usual gait speed (m/s)	1.10 $\pm$ 0.24	0.54 to 1.59
F8W: time to complete (s)	9.5 $\pm$ 2.5	6.0 to 18.31
F8W: No. of steps	17 $\pm$ 3.4	9 to 27

Abbreviations: MMSE, Mini-Mental State Examination; NA, not applicable.

Table 2

Correlation Coefficients for Relations of Age, Executive Function, and Straight- and Curved-Path Walking (N=106)

Variable	DSST	TMT-A	TMT-B	TMT-B-A	Usual Gait Speed	F8W: Time to Complete	F8W: No. of Steps
Age	-.186	.198 *	.205 *	.157	-.357 †	.379 †	.339 †
DSST		-.448 †	-.454 †	-.332 †	.315 †	-.308 †	-.201 *
TMT-A			.299 †	.021	-.325 †	.336 †	.261 †
TMT-B				.960 †	-.280 †	.256 †	.408 †
TMT-B-A					-.198 *	.169	.325 †
Usual gait speed						-.727 †	-.699 †
FBW: time to complete							.771 †

* $P < .05$.

† $P < .01$.

Table 3

Linear Regression Model Summary for Straight- and Curved-Path Walking (N=106)

Independent Variables	Straight-Path Walking Usual Gait Speed β (<i>P</i>)	Curved-Path Walking	
		F8W: Time to Complete β (<i>P</i>)	F8W: No. of Steps β (<i>P</i>)
Model 1			
Age	-.334 (<.001)	.372 (<.001)	.367 (<.001)
Sex	-.179 (.052)	.204 (.028)	.203 (.032)
DSST	.261 (.005) *	-.190 (.042) *	-.117 (.217)
Model 2: Additional variance explained by TMT-A			
Age	-.302 (.001)	.333 (<.001)	.327 (.001)
Sex	-.181 (.045)	.206 (.023)	.204 (.026)
DSST	.201 (.033) *	-.126 (.177)	-.050 (.596)
TMT-A	-.222 (.017) *	.247 (.008) *	.257 (.007) *
Model 2: Additional variance explained by TMT-B			
Age	-.312 (.001)	.349 (<.001)	.320 (.001)
Sex	-.179 (.050)	.204 (.027)	.202 (.026)
DSST	.208 (.033) *	-.143 (.143)	-.020 (.832)
TMT-B	-.159 (.099)	.148 (.125)	.300 (.002) *
Model 2: Additional variance explained by TMT-B-A			
Age	-.324 (.001)	.363 (<.001)	.341 (<.001)
Sex	-.178 (.053)	.204 (.028)	.202 (.029)
DSST	.236 (.015) *	-.171 (.077)	-.059 (.534)
TMT-B-A	-.093 (.321)	.074 (.429)	.221 (.019) *

Abbreviation: β , standardized coefficients.

* Cognitive function variables that contributed to the explained variance in walking.