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RESEARCH ARTICLE

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Walking is more like catching than tapping: gait in the elderly as a complex cognitive task

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Abstract Walking is generally viewed as an automated, over-learned, rhythmic motor task and may even be considered the lower-limb analog of rhythmic finger tapping, another automated motor task. Thus, one might hypothesize that walking would be associated with a simple rhythmic task like tapping rather than with a complex motor task like catching. Surprisingly, however, we find that among older adults, routine walking has more in common with complex motor tasks, like catching a moving object, than it does with tapping. Tapping performance, including both the average tapping interval and the variability of tapping interval, was not significantly associated with any gait parameter (gait speed, average stride time and stride time variability). In contrast, catch game performance was significantly associated with measures of walking, suggesting that walking is more like catching than it is like tapping. For example, participants with a higher gait speed tended to have lower times to first move when catching, better catching accuracy, and less catching errors. Stride time variability was significantly associated with each of the measures of catching. Participants with a lower stride time variability (a more steady gait) had better catching accuracy, lower time to first move, fewer direction changes when moving the cursor to catch the falling object, and less catching errors. To understand this association, we compared walking performance to performance on the Stroop test, a classic measure of executive function, and tests of memory. Walking was associated with higher-level cognitive resources, specifically, executive function, but not with memory or cognitive function in general. For example, a lower (better) stride time variability was significantly associated with higher (better) scores on the Stroop test, but not with tests of memory. Similarly, when participants were stratified based on their performance on the Stroop test and tests of memory, stride time variability was dependent on the former, but not the latter. These findings underscore the interconnectedness of gait and cognitive function, indicate that even routine walking is a complex cognitive task that is associated with higher-level cognitive function, and suggest an alternative approach to the treatment of gait and fall risk in the elderly.

Keywords Gait · Cognitive function · Aging · Rhythmicity · Variability

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Background

As suggested by the title of one of the classic texts on gait, "Muscles, Reflexes and Locomotion" (McMahon 1984), the general dogma is that walking is a ballistic, automatic motor task. Decerebrate cats walk (Burke et al. 2001; Shefchyk and Jordan 1985), supported newborns move their legs in a normal walking pattern (Lamb and Yang 2000), and adults ambulate with ease even as they juggle cognitively demanding tasks. Apparently, central pattern generators (Burke et al. 2001; Lamb and Yang 2000; Shefchyk and Jordan 1985), or their equivalents, create the rhythm and gait proceeds under the stewardship of the motor control system utilizing little, if any, cognitive resources. Thus, walking—more specifically routine, over-learned gait—may be considered the lower-limb analog of rhythmic finger tapping, another motor task that is rhythmic, automatic and has little dependence on cognitive function. Indeed, imaging studies have shown that walking (Fukuyama et al. 1997) and rhythmic tapping are primarily regulated by the basal ganglia, the supplementary motor area, and the cerebellum (Riecker et al. 2003).

Although walking has long been considered primarily as an automatic motor task, an emerging body of evidence suggests that this view may be too simplistic. Rather, cognitive function may play a key role in the regulation of even routine walking. Epidemiologic evidence indicates that, among older adults, fall risk increases in those with impaired cognitive function (AGS 2001) and the stability of gait and balance may decline in certain populations when subjects are asked to walk and perform a second task (dual tasking) (Bloem et al. 2001; Sheridan et al. 2003; Woollacott and Shumway-Cook 2002). An exacerbated dual-task decrement in walking ability has been observed in idiopathic elderly fallers, in patients with Parkinson's disease (primarily a motor disorder), and in patients with Alzheimer's disease (primarily a cognitive disorder) (Bloem et al. 2001; Sheridan et al. 2003; Woollacott and Shumway-Cook 2002). Some investigators have proposed that changes in executive function—a cognitive domain that enables the juggling of multiple tasks and the regulation of complex cognitive responses—are responsible for the dual task decrement observed in certain elderly populations (Cocchini et al. 2004; Sheridan et al. 2003).

Here we take this suggestion a step further and ask two related questions:

1. Is routine walking like tapping, a simple automated, motor task with minimal cognitive involvement, or is it more like catching, a complex motor task with higher-level cognitive involvement (Schenk et al. 2004; Montagne et al. 1999)?
2. Does routine walking rely upon executive function?

While the performance of more complex motor tasks is affected by cognitive function (Gnanalingham et al. 1997), finger tapping rate is normal even in patients with mild dementia (Goldman et al. 1999). Like tapping, rhythmicity is a key feature of walking. However, during ambulation, numerous sensory and conscious inputs and competing objectives (for example, upright posture versus locomotion) are seamlessly integrated across hierarchical systems, all while subtle real-time decisions and adjustments are being made. From this perspective, routine walking may be viewed as a dual or multi-task. Thus, we hypothesized that even routine, steady-state walking utilizes cognitive resources, specifically executive function, and therefore that it would be more closely associated with catching than with tapping.

Materials and methods

Participants and protocol

To test these hypotheses, we studied a group of non-demented, ambulatory older adults. Specifically, we quantified the gait, tapping and catching skills of a group of 43 older adults (ages 62–86 years; mean: 71.9 years; 22 women) with a broad range of abilities in each area. Older adults were recruited from the community. Participants were included if they were non-demented, according to DSM IV criteria (for example, Mini-Mental State Exam (MMSE) (Folstein et al. 1975) scores were all ≥27), and were free from gait and cognitive disturbances, neurological, affective, orthopedic or other co-morbidities likely to impact gait, as verified by medical history and physical exam. Participants were at least 60 years old, were living independently in the community, and were able to walk without ambulatory aids or assistance. The study was approved by the Human Studies Committee of the Tel-Aviv Sourasky Medical Center. All volunteers provided informed written consent according to the Declaration of Helsinki prior to entering the study.

After providing informed consent and undergoing a brief physical and history, extra-pyramidal and motor signs were quantified using the motor portion of the Unified Parkinson's Disease Rating Scale (UPDRS-motor) (Fahn et al. 1987). This test quantifies common motor signs of aging (such as bradykinesia) and predicts gait disability and mortality in non-demented older adults free of Parkinson's disease (Bennett et al. 1999; Wilson et al. 2002). A score of 0 (out of a possible 108) on the UPDRS-motor scale is optimal. Subsequently, participants walked up and down a 25 m-long, 2 m-wide hallway at their self-selected, usual walking speed for 2 min while wearing force-sensitive sensors. Average values and the coefficient of variation (CV) of the stride time (the gait cycle duration) were determined using previously described methods that quantify the dynamics of steady-state walking and filter "outliers" (for example, due to turns) (Hausdorff et al. 2001; Sheridan et al. 2003). The CV assesses the stride-to-stride variability or (dys)rhythmicity of gait, a measure previously associated with fall risk (Hausdorff et al. 2001; Maki 1997; Schaafsma et al. 2003). Each subject's CV is defined as 100×(standard deviation of stride time/mean stride time). Average gait speed was also determined by measuring the time to walk 10 m. To minimize start-up and to characterize steady-state walking, gait speed was quantified over the middle 10 m of the walkway. Average gait speed has been associated with and been shown to predict disability and health outcomes among older adults (Guralnik et al. 2000; Jylha et al. 2001).

A computerized cognitive assessment system, Mindstreams, (NeuroTrax Corporation, NY, USA), was used to evaluate tapping, catching, and cognitive function (Dwolatzky et al. 2003; Schweiger et al. 2003). To assess tapping abilities, participants were instructed to tap on the mouse button with their dominant hand for 12 s. The average inter-tap interval (the time between consecutive taps) and tapping variability (the CV) were quantified. To avoid any start-up effects and to measure steady-state performance, the first 2 s of data were not included in the analyses of tapping. The average of two trials was used. An arcade-like computer game was used to assess (to some degree) catching abilities, so that the tapping and catching tasks were similar with respect to the muscle function required, but differed primarily with respect to the nature of the task and the cognitive resources required (rhythmic tapping versus planning and continuous decision making). In the catch game (Dwolatzky et al. 2003; Schweiger et al. 2003), participants must "catch" a rectangular white object falling vertically from the top of the computer screen before it reaches the bottom of the screen. Mouse button presses move a rectangular green "paddle" horizontally so that it can be positioned directly in the path of the falling object. The test requires hand-eye coordination, scanning and rapid responses. Catch game measures included time to first move (time until initial response), number of direction changes of the paddle, accuracy, and degree of errors (number of "paddle" units away from the falling object).

Two additional tests of cognitive function were administered (Dwolatzky et al. 2003): (1) the Stroop test, and (2) a test of verbal memory. The Stroop is a well-established cognitive test (MacLeod 1991; Langenecker et al. 2004) of executive function that measures the facility with which an individual can shift his or her perceptual set to conform to changing demands and suppress a habitual response in favor of an unusual one (MacLeod 1991; Spreen and Strauss 1988). In the first ("No Interference [Color]") phase, participants choose the letter-color of a general word. In the next ("No Interference [Meaning]") phase, the task is to choose the color named by a word presented in white letter-color. In the final ("Interference") phase, participants choose the letter-color of a word that names a different color. To assess executive function, we evaluated accuracy, reaction time, and a composite score (100×accuracy/reaction time) that takes into account speed-accuracy trade-offs during the final (interference) Stroop phase. Verbal memory was also assessed to see if any effects observed with the Stroop test were specific to this cognitive domain. Verbal memory generally does not require executive function. Briefly, ten pairs of words were presented, followed by a recognition test in which one member (the target) of a previously presented pair appears together with a list of four candidates for the other member of the pair. Participants indicate which word of the four alternatives was paired with the target when presented previously. Four consecutive repetitions of the recognition test were administered during the "learning" phase. The accuracy during each phase and the average accuracy across all phases were determined. An additional recognition test was administered following a delay of approximately 10 m. Previous work has shown that these computer-based versions of classic neuropsychological tests have good concurrent validity and reliability and are highly correlated with performance on traditional neuropsychological batteries (Dwolatzky et al. 2003; Schweiger et al. 2003). Finally, the MMSE was used as a screening tool as well as a gross measure of cognitive function.

Statistical analyses

Descriptive statistics are reported as mean ± SD. Pearson's correlation coefficients were used to quantify the bivariate association between variables. The Student's *t*-test was used to compare two groups. To minimize the chances of obtaining false-positive associations, a *p*-value (two-sided) less than or equal to 0.013 was considered statistically significant (Bonferroni-like adjustment for the three measures of gait; unadjusted *p*-values are reported).

Results

Subject characteristics

Table 1 summarizes the basic characteristics of the 43 participants studied. Participants had a mean age of 72 years, were generally educated, and had near-perfect scores on the MMSE. As expected, UPDRS-motor scores were close to 0 (in other words, optimal), and similar to those seen in previous studies of healthy older adults (Herman et al. 2005). Tables 2 and 3 summarize the walking and cognitive function of the study cohort. Walking measures were similar to those seen in other studies of healthy older adults (Hausdorff et al. 1998; Kerrigan et al. 1998). There was a fairly large intra-group variation for walking, catching, tapping and cognitive function (notice the sizes of the standard deviations).

Associations between walking, tapping and catching

Table 4 shows the relationship between walking, on the one hand, and tapping and catching, on the other. Tapping performance, both the average tapping interval

Table 1 Characteristics of the participants[a]

Age (years)	71.9 ± 6.4
Gender (number of women)	22
Education (years)	13.7 ± 2.1
Height (m)	1.67 ± 0.08
Weight (kg)	72.5 ± 11.5
UPDRS-motor	1.3 ± 1.5
MMSE	29.0 ± 1.1

[a] Values reported are mean ± SD, except for gender. UPDRS-motor is the score on the motor part of the Unified Parkinson's disease Rating Scale. *MMSE* Mini Mental State Exam

Table 2 Walking, catching and tapping performance

Walking	Average gait speed (m/s)	1.11 ± 0.28
	Average stride time (s)	1.09 ± 0.09
	Stride time variability (%)	2.0 ± 0.6
Tapping	Tapping rate (ms)	235 ± 49
	Variability of tapping (%)	16.2 ± 8.9
Catching	Time to first move (ms)	1217 ± 822
	Number of direction changes	0.7 ± 1.3
	Accuracy (arb. units)	435 ± 290
	Errors (paddle units)	1.6 ± 1.9

Table 3 Summary of cognitive performance

Stroop test	Accuracy (%)	75.1 ± 32.3
	Response time (ms)	810 ± 363
	Composite index	11.2 ± 6.9
Memory	Immediate recall (%)	50.8 ± 31.3
	Recall during 4th trial (%)	73.9 ± 31.9
	Average recall (across four trials, %)	65.4 ± 29.8
	Delayed recall (after 10 min, %)	68.9 ± 31.0

Table 4 Correlations between walking and tapping and between walking and catching[a]

	Walking		
	Average gait speed	Average stride time	Stride time variability
Tapping			
Average tapping interval	NS	NS	NS
Variability of tapping interval	NS	NS	NS
Catching			
Time to first move	NS	NS	0.43 (0.004)
Number of direction changes	NS	NS	0.43 (0.005)
Accuracy	0.38 (0.013)	NS	−0.42 (0.006)
Degree of errors	NS	NS	0.44 (0.004)

[a] Entries are Pearson correlation coefficients (*p*-values). *NS* denotes $p > 0.013$. For catching accuracy, higher scores reflect better performance, but for other measures of catching, lower scores correspond to better performance

and the variability of tapping interval, was not significantly associated with any gait parameter ($p > 0.07$). In contrast, catch game performance was significantly associated with measures of walking, suggesting that walking is more like catching than it is like tapping. For example, participants with a higher gait speed tended to have lower times to first move when catching ($p = 0.025$), better catching accuracy ($p = 0.013$), and less catching errors ($p = 0.049$). Stride time variability was significantly associated ($p \leq 0.006$) with each of the measures of catching. Participants with a lower stride time variability (a more steady gait) had better catching accuracy, lower time to first move, fewer direction changes when moving the cursor to catch the falling object, and fewer catching errors.

The associations between walking and catching measures generally persisted after adjusting for age, gender, height, weight or years of education in multiple regression analyses that included any of these subject characteristics that were marginally ($p < 0.10$) related to catching and walking. In multiple regression models, gait speed was associated with catch game time to first move and accuracy, and stride time variability continued to be associated with all catch game measures.

Associations between walking and cognitive function

To better understand why walking was associated with catching, we examined the relationship between walking and the Stroop test and walking and tests of memory. The Stroop test taxes decision-making abilities and reaction time, skills required to catch a moving object (Schenk et al. 2004; Montagne et al. 1999), while memory does not. Performance on the Stroop test was correlated with some of the measures of gait (Table 5). A lower (better) stride time variability was associated with higher (better) scores on the Stroop test composite index ($r = -0.42$; $p = 0.009$). The Stroop test was also significantly associated with performance on the catch game, demonstrating (or confirming) that the catch game has a strong executive function component (for example, correlation between Stoop test and catch game accuracy: $r = 0.51$, $p < 0.001$). In contrast, no measures of verbal memory were correlated ($p > 0.11$) with any measure of walking. The three measures of gait were not associated with MMSE scores ($p > 0.15$).

We examined whether the observed effects (Table 5) persisted after adjustment for age, gender, height, weight and/or education. In multiple regression analyses that

Table 5 Association between measures of cognitive function and gait

	Stroop test performance			Memory		
	Accuracy	Reaction time	Composite index	Immediate recall	Average over four trials	Delayed recall
Average gait speed	NS	NS	NS	NS	NS	NS
Average stride time	−0.41 (0.009)	NS	−0.44 (0.005)	NS	NS	NS
Stride time variability	NS	NS	−0.42 (0.009)	NS	NS	NS

[a] *NS* denotes $p > 0.013$. Entries are Pearson correlation coefficients (*p*-values). None of the measures of memory (for example, immediate recall, accuracy after 10 min) were associated with any of the walking measures ($p > 0.11$)

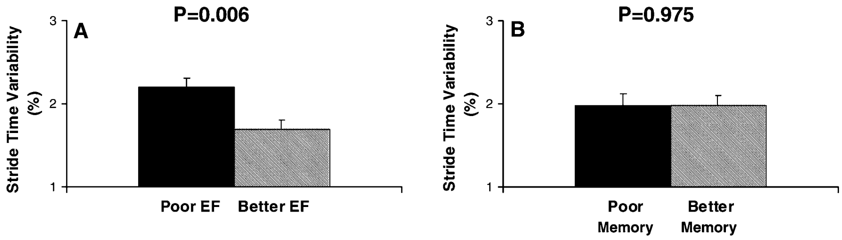

Fig. 1A–B Dependence of walking on executive function, but not memory. **A** Participants were stratified based on their performance on the Stroop test into those who performed in the top 50% (Better EF) and those in the bottom 50% (Poor EF). Stride time variability was significantly different in those with Poor EF compared to subjects with Better EF. Shown are the results when *Stroop test* stratification was based on the composite score; similar results were obtained if stratification was based on Stroop test accuracy. *Error bars* reflect the standard error of the mean. **B** In contrast, when participants were stratified based on verbal memory (all measures; here the results are shown for the test after a 10 min delay), the three measures of walking were not different in those who did poorly and those who did better on tests of memory ($p > 0.18$ for all gait measures)

included any of these subject characteristics that were marginally ($p < 0.10$) related to gait and Stroop test performance, the association between stride time variability and the Stroop test was preserved. On the other hand, the association between the Stroop test and the average stride time was no longer significant in a multivariate model.

As shown in Fig. 1, the dependence of walking on cognitive function, in particular executive function (EF), is underscored if we stratify the data based on the Stroop test (composite index or accuracy) and compare the performance of those with the lowest performance (bottom 50%: Poor EF) to those with the best performance (top 50%: Better EF). Compared to those in the Poor EF group, stride time variability was significantly lower in those in the Better EF group ($p = 0.006$). For both stratifications, average stride time also tended to be different in those with better EF compared to those with worse EF (for example, $p = 0.021$ when participants were stratified using Stroop accuracy). When stratified by Stroop reaction time, gait speed tended to be different in those with better and worse times ($p = 0.011$), but the other two gait measures were not. Compared to those in the Poor EF group, the Better EF group also performed better on all measures of catching (for instance, $p < 0.008$ when stratified using the Stroop composite index; similar results were obtained when participants were stratified with respect to Stroop reaction time or accuracy). Except for immediate recall, which tended to be different in those with better and worse EF ($p = 0.035$), all other measures of memory and the MMSE scores were not different in Poor EF and Better EF (for example, $p = 0.49$ for delayed memory, and $p = 0.30$ for the MMSE). In contrast to stratification by EF, when participants were stratified based on memory (such as average accuracy across all trials or delayed recall), walking (all measures) was not different in those who did poorly and those who did better on tests of memory.

Discussion

To our knowledge, the results of the present study provide, for the first time, evidence that routine walking can be considered as a relatively complex task that involves higher-level cognitive input. In non-demented older adults, we compared usual walking to both a simple, automated motor task and a complex motor task. We find that walking performance is more like catching, an act that utilizes complex cognitive resources and executive function (such as estimation, planning, real-time adjustments) than it is like tapping. Moreover, we demonstrate that routine walking and walking-derived markers of fall risk are significantly associated with performance on specific cognitive domains, namely the Stroop test, a classic measure of executive function, but not with memory or cognitive function in general.

Previous work has shown that, in older adults, performance of complex movements such as walking through an obstacle course is associated with problem solving and executive function, but not with memory (Gnanalingham et al. 1997; Persad et al. 1995). The present findings are almost identical except for a key difference. Here we provide evidence that even relatively simple, steady-state walking may be a complex task that is related to higher cognitive function (EF). Walking behaves more like a complex motor task than an automated, rhythmic motor task. Similarly, some studies in demented older adults have suggested that changes in gait are due to impairment of executive function (Cocchini et al. 2004; Sheridan et al. 2003) and the results of "dual tasking" investigations suggest that walking may require attention and utilize cognitive function. Here we extend these ideas. The present cohort was not demented and had intact general cognitive function (recall that mean MMSE scores were 29) as well as relatively good walking abilities. Mean gait speed, average stride time, and stride variability were similar to norms reported for this age (Kerrigan et al. 1998; Schaafsma et al. 2003; Hausdorff et al. 1998). We did not study a complex, locomotor task or dual tasking; participants walked at their usual pace on level ground. The present findings indicate that, even among non-demented older individuals with good general cognitive function and walking abilities, usual, routine gait may require executive function.

If newborns are able to generate a stepping pattern and decerebrate cats are able to ambulate, why is gait in older adults more like a complex cognitive task that requires higher-level cognitive input? A number of explanations have been proposed to understand dual-task decrements in the elderly, in general, and why the performance of a secondary task influences the balance and gait of older adults (Brown and Marsden 1991; Della Sala et al. 1995; Szameitat et al. 2002). Perhaps these can be extended to explain why routine walking is associated with tests of executive function. According to one theory, when two simultaneously performed tasks compete for insufficient attention, a decline in task performance will be observed when attentional-capacities are exceeded. As noted above (in the "Background" section), one could suggest that even routine walking has features of a dual or multi-task. Among older adults, subtle changes in motor control and sensory feedback systems might lead to diminished automaticity of gait and generate a need for cognitive supervision in order to properly integrate all of the sensory information and regulate dynamic balance and gait. This multi-tasking may require executive function, especially the ability to allocate attention among multiple challenges. The Stroop test assesses one's ability to shift attention and adapt to changing demands. Consistent with this idea, the Stroop test was associated with performance on a complex motor task, like catching, and with routine walking, but tests of memory were not. Future investigations should more fully address this question, perhaps in part by determining whether the observed association between gait and cognitive function is specific to aging or whether this association is also observed in healthy young adults.

Among the three measures of gait, stride time variability tended to be most closely associated with catching game performance (Table 4) and the Stroop test (after accounting for subject characteristics). This aspect of gait reflects the neural control system's ability to maintain a steady walking rhythm. One might have hypothesized that regulation of gait rhythmicity would be associated with tapping rhythmicity, but this was not observed. The association with catch game performance, but not with tapping variability, is in line with the view that regulation of a steady walking rhythm requires "real-time control" and executive control. Perhaps this explains, in part, why stride-to-stride variability of gait is associated with fall risk (Hausdorff et al. 2001; Maki 1997; Nakamura et al. 1996; Schaafsma et al. 2003) and why dual-tasking increases stride variability among subjects with executive function deficits (Hausdorff et al. 2003; Sheridan et al. 2003). To prevent falling, one needs to be able to maintain a steady walking rhythm and use real-time control to adapt to any perturbations and postural challenges.

Taken together, the present findings provide important new insight into motor control, gait, and falls. Typically, gait and cognitive function are studied in separate disciplines as more or less distinct processes. Here we provide somewhat counter-intuitive evidence that belies this perspective and leads to new thinking about these two essential functions. The present findings suggest that, in addition to the traditional approach to the study and treatment of gait, efforts should also be focused on the role of cognitive function. Perhaps the study of gait and motor control should also include neurocognitive aspects as well as the study of muscles and reflexes. Hopefully, these findings will pave the way and motivate future cross-disciplinary studies that will help us to better understand the bridges and interdependence between cognitive function and gait.

One might argue that the results of the present study are fairly obvious. Older adults who walk better do better on tests of cognitive function, perhaps because physiologic aging has similar effects on these two systems. As shown in Fig. 1 and Tables 4 and 5, however, it is not simply that better gait correlates with better cognitive function. Memory and a general marker of cognitive function were not related to routine walking performance. Our findings indicate that there is specificity to the relationship between gait and cognitive function and suggest that gait is a relatively complex motor task that requires executive function.

Walking and rhythmic finger tapping share many of the same characteristics (being seemingly automatic, periodic) and are regulated by many of the same neural networks (such as basal ganglia, cerebellum) (Fukuyama et al. 1997; McMahon 1984; Riecker et al. 2003). Some might go so far as to suggest that walking is an over-learned motor task that requires minimal cognitive overhead. Walking, however, is apparently a much more complex task that shares more with catching than it does with tapping, at least among older adults. Evidently, simple walking is associated with and may depend upon complex cognitive input including certain aspects of executive function, but does not necessarily require other cognitive domains such as memory. These findings shed light on a number of observations that have yet to be fully explained. If walking is a challenging motor task like catching and relies upon executive function, it now follows: (1) that persons with impaired EF have a disturbed gait and an increased fall risk and (2) that dual-tasking perturbs gait (for instance, it increases stride-to-stride variability) and exacerbates fall risk in sub-groups of older adults such as patients with Parkinson's disease, Alzheimer's disease, or idiopathic fallers (Bloem et al. 2001; Sheridan et al. 2003; Woollacott and Shumway-Cook 2002; Camicioli et al. 1997). When two tasks that require cognitive input are performed simultaneously, executive function is needed to allocate the appropriate cognitive resources to each. Thus, a dual-task decrement may be observed when a secondary task is performed during walking. In patients with marked impairment of executive function (such as advanced Alzheimer's disease), one might anticipate a ceiling effect such that gait would *not* be affected by dual tasking, but this has not been observed (Sheridan et al. 2003).

The idea that executive function is critical to walking might also partially account for the intriguing results of recent prospective studies which reported that impaired mobility—not attributable to a specific disease—predicts future dementia as much as six years into the future (Verghese et al. 2002; Marquis et al. 2002). The present findings also suggest the possibility that interventions designed to improve executive function (Giladi et al. 2003) might enhance gait and reduce the fall risk of older adults. More generally, our data provide further evidence that there is much more to gait than automated musculo-skeletal movements.

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