

The Role of Executive Function and Attention in Gait

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Abstract: Until recently, gait was generally viewed as a largely automated motor task, requiring minimal higher-level cognitive input. Increasing evidence, however, links alterations in executive function and attention to gait disturbances. This review discusses the role of executive function and attention in healthy walking and gait disorders while summarizing the relevant, recent literature. We describe the variety of gait disorders that may be associated with different aspects of executive function, and discuss the changes occurring in executive function as a result of aging and disease as well the potential impact of these

changes on gait. The attentional demands of gait are often tested using dual tasking methodologies. Relevant studies in healthy adults and patients are presented, as are the possible mechanisms responsible for the deterioration of gait during dual tasking. Lastly, we suggest how assessments of executive function and attention could be applied in the clinical setting as part of the process of identifying and understanding gait disorders and fall risk. © 2007 Movement Disorder Society

Key words: gait; executive function; attention; Parkinson's disease; Alzheimer's disease; aging; dual task; review article

The relationship between higher-level cognitive function and gait disturbances has received considerable attention in recent years. Gait is no longer considered as merely an automated motor activity that utilizes minimal higher-level cognitive input. Instead, the multifaceted neuropsychological influences on walking and the interactions between the control of mobility and related behaviors are increasingly appreciated. This is manifest in part by an individual's awareness of a destination, the ability to appropriately control the limb movements that produce gait, and the ability to navigate within often complex environs to successfully reach the desired location. Studies on cognitive function and gait now include many areas of

research, ranging from physiology and biomechanics to brain mapping, physics and neuropsychology. For example, imaging studies have demonstrated frontal and parietal activity during locomotion.^{1,2} This review covers the importance and relevance of two specific cognitive functions, executive function (EF) and attention, to the performance of gait during normal walking, as well as in aging and in pathological conditions. We review the physiology underlying these cognitive processes, describe the clinical findings and consequences of these relationships and discuss the physiological mechanisms that are brought into play. Finally, we summarize the implications of these associations for the daily lives of individuals affected by impaired function of one or more of these elements and provide suggestions for applying these insights to augment the diagnosis of gait disorders in the clinic.

This review article is based on a systematic literature search for reviews and trials reported in English in the electronic databases of Medline and Psycinfo up to April, 2007. Relevant studies were identified by first searching using combinations of the following key words: gait (or walking), cognition (or cognitive), dual task, divided attention, EF, and aging. We also examined "related articles" and relevant cited works.

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EXECUTIVE FUNCTION

EF refers to a variety of higher cognitive processes that use and modify information from many cortical sensory systems in the anterior and posterior brain regions to modulate and produce behavior.³⁻⁶ These integrative functions include both cognitive and behavioral components that are necessary for effective, goal-directed actions and for the control of attentional resources, which are at the basis of the ability to manage independent activities of daily living (ADL).^{5,7,8}

Lezak divided EF into four major components: volition, planning, purposive action and effective performance (action monitoring).⁵ Others also explicitly include cognitive inhibition as an EF component.⁷⁻⁹ Impairment of one or more of these components of EF may impact one's ability to walk efficiently and safely. Poor self-awareness of limitations, an aspect of volition, might result in an increased risk of falling.¹⁰ Impaired planning skills could result in getting lost or choices that produce inefficient pathways or unnecessary effort to arrive at a destination. Table 1 summarizes the main components of EF and their potential effects on gait.

The Normal Anatomy and Physiology of EF

EF is traditionally associated with the frontal lobes and related brain networks. The area of the prefrontal

lobe and, in particular, the dorsolateral prefrontal cortex (DLPFC, Brodmann's area 9) and the cingulate cortex (e.g., the anterior cingulate: ACC, Brodmann's areas 24, 32) have been related to the cognitive aspects of EF.^{5,7-9} Patients with frontal damage frequently display impairments in cognitive functions attributed to EF, although activation of other brain areas, such as the parietal lobe, association areas and subcortical areas, including the limbic areas, are also attributed to EF.^{5,7-9,16} In general, the anterior parts of the frontal lobes are involved with aspects of self-regulation, such as inhibition and self-awareness, whereas the dorsal parts are involved with reasoning processes.

Neuroimaging studies attempting to localize the activity of EF report inconsistent findings. Collette et al. reviewed investigations that explored the neural substrates of EF, focusing on specific aspects, such as response inhibition and dual task coordination.¹⁶ They found that different EF tasks not only activated different frontal and parietal areas, they also activated other areas of the brain. This supports the hypothesis that EF is based on a network of anterior and posterior cerebral areas and is not localized only to the frontal cortex.¹⁶ Stuss and Alexander argued that the common use of the term "frontal function" (or "frontal syndrome") as a synonym for EF is not accurate, because of the many

TABLE 1. *Executive function (EF) components and their possible effects on gait disorders: a theoretical view*

EF Component	Description of component	Effect on gait (when this component is impaired)
Volition	The capacity for intentional behavior, for formulation of a goal or intention, and for initiation of activity ⁵	Loss of mobility due to reduced motivation. Decreased inner drive to move. May be mistaken for bradykinesia.
Self-awareness	The ability to place oneself (psychologically and physically) in the physical environment and the ongoing situation ⁵	Careless walking: Poor or inaccurate estimation of one's physical limitations may lead to inappropriate evaluation of environmental hazards and increase the risk of falling.
Planning	"The identification and organization of the steps and elements needed to carry out an intention." ⁵ This may rely on other cognitive skills such as the ability to conceptualize changes from present circumstances, conceiving alternatives, weighing, and making choices, controlling impulses and using memory ^{5,11}	Deficits in decision-making abilities while walking in a complex environment. Inefficient, faulty or even risky choices. Losing the way or wasting time or effort to arrive at the desired destination.
Response inhibition	Allows one to ignore irrelevant sensory inputs, overcome primary reflexes, and filter out distractions to solve problems and respond discriminatively to important features in the environment. ^{11,12} This ability is closely related to selective attention.	When walking in complex, everyday environments, response inhibition allows one to focus on gait and give it the appropriate attention and priority, despite numerous distractions.
Response monitoring	Enables one to compare ongoing actions with an internal plan and to detect errors. ^{12,13} This skill facilitates decision making and the flexible adjustment of behavior ¹²	This EF component may also be important for walking in complex environments. Demented patients may walk too fast, increasing their risk of falls, because of reduced inhibition. ¹⁰ Performance on classical tests of response inhibition and response monitoring, the Stroop and the Go No-Go tests, have been associated with gait variability. ^{14,15}
Attention/dual tasking	The ability to appropriately allocate attention among tasks that are performed simultaneously.	See Table 2

methodological problems in the studies that tried to explore associations between the two.¹⁷ In support of that claim, a meta-analysis found that three classical tests of EF (i.e., the Wisconsin Card Sorting, the Stroop, and the verbal fluency tests) were sensitive to frontal lobe damage, but other areas of the brain could also lead to poor performance in these tests.¹⁸ The authors suggested “that the frontal lobes participate to a greater extent than other areas of the brain in functions considered to be executive.”¹⁸ Thus, patients who do not have a frontal lesion might demonstrate impairments in components of EF and display “cognitive” gait disorders. In summary, the frontal lobes and closely related networks play a critical role in EF, but other areas also contribute to this cognitive domain.

EF and the Aging Process

The frontal lobes are apparently highly susceptible to age-associated changes.^{8,11,19} These include lesions of diffused white matter, which might affect fronto-striatal circuits and cause, among other things, impairment in EF.²⁰ A meta-analysis by Gunning-Dixon and Raz revealed that white matter hyper-intensities on magnetic resonance imaging (MRI) were associated with a decline of processing speed, EF, and memory, but not with the level of general intelligence.²¹ Other studies support these findings and emphasize the vulnerability of EF to white matter lesions.²²⁻²⁴ Additional brain pathology, such as loss of dendritic branching (especially in the prefrontal cortex)²⁵ and changes in the gray matter (mainly tissue loss) are also associated with decline in performance on EF tests.^{20,21,26} Age-associated decline in dopaminergic activity in the frontal areas is also related to poorer performance on executive tasks.^{23,25,26} As mentioned earlier, it is, however, important to keep in mind that EF changes may be the result of alterations in areas other than just the frontal lobe.

In parallel to these anatomical changes, neuropsychological studies demonstrated impaired EF in generally healthy elderly subjects. This includes difficulties in problem solving that requires flexible thinking and cognitive shifting, impaired response inhibition, and impaired creative thinking.¹⁹ There is, however, a great variability of these frontal brain changes among aging individuals in terms of the magnitude, age when changes occur, and the influence of education and lifestyle.^{20,26} Although it is generally agreed that there is an overall cognitive slowing with aging, and that there is a decline in some aspects of EF, such as mental flexibility, abstract thinking, and attention, this does not necessarily reach the level of “dysfunction” and there is no consensus regarding the precise pattern of altered EF that results

from age-associated changes.⁵ Based on the literature and our clinical experience, we suggest that EF is generally persevered in healthy and normal aging, although some components, like attention, show subtle decline. Therefore, in a clinical setting, the determination of EF impairment should be carried out with caution, since decline in some EF domains should not lead to sweeping generalizations. Further, conclusions on EF status should not be made on the basis of neuropsychological test scores alone, but should also include the individual’s abilities to carry out ADL that tax EF successfully. Meal preparation and grocery shopping are two common ADL that typically rely on EF.

Correlation of EF Testing and Gait Measures

Several investigations have attempted direct study of the relationships between EF and gait abilities. In the InChanti study, over 900 nondemented older adults (mean age 74.6 ± 6.7 years, MMSE 25.5 ± 2.8) walked at a self-selected speed and at a fast speed over an obstacle course.²⁷ To assess EF, subjects also performed the Trail Making Test (TMT), a classic test of EF. Briefly, the TMT is a visuomotor timed task that is used routinely in clinical evaluations and has a dimension of cognitive flexibility. The test consists of two parts: TMT-A and TMT-B. TMT-A is a simple visual-scanning task that requires one to draw a line connecting consecutive numbers from 1 to 25. TMT-B adds a dimension of cognitive flexibility by requiring the subject to draw a line connecting numbers and letters in an alternating sequence. Subjects in the InChanti study were divided into three groups on the basis of their performance on the TMT: poor, intermediate and good.²⁷ Poor and intermediate performance on the TMT was associated with decreased gait speed on the obstacle course (see Fig. 1), although the mean speeds in all three groups were within normal limits. The authors concluded that EF is critical in complex gait situations. A follow-up study in this cohort also found associations between the effects of other dual tasks on walking performance and TMT scores.²⁸

Similar findings were reported by Holtzer et al.²⁹ They demonstrated associations between performance on a cognitive test battery and gait speed. The cognitive battery assessed speed of processing, attention, memory, language and EF. Both EF and memory were correlated with gait speed under dual task conditions, whereas verbal IQ was not. Those authors suggested that gait in the elderly is a complex task requiring higher control of executive processing and memory. Springer et al.¹⁴ and Yogev et al.¹⁵ reported weak associations between EF and gait variability under usual walking conditions that

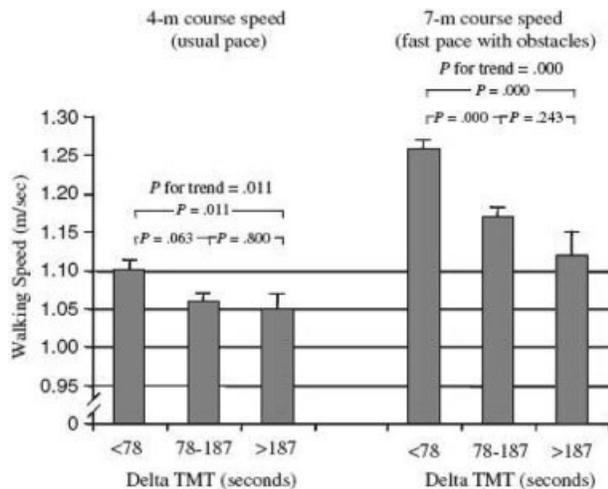


FIG. 1. Association between gait speed and performance on the TMT in the InCHIANTI study. Subjects with poor and intermediate performance in the TMT (i.e., large increase when going from TMT-A to TMT-B) had decreased gait speed, especially on the obstacle course. From Ble et al.²⁷

became stronger under dual tasks conditions among elderly nondemented fallers and among patients with Parkinson's disease, whereas such associations were not observed in healthy young adults. Similarly, Hausdorff et al. showed that better gait performance (e.g., higher gait speed, lower stride time variability) was associated with better scores on a "catch game," a complex motor task, but this association did not exist for finger tapping, a relatively simple motor task.³⁰ Associations between EF and performance of balance and mobility were also observed in stroke patients, even after adjustment for age, quadriceps strength of the paretic side and current physical activity level.³¹

The earlier mentioned studies demonstrate how gait is related to EF. It appears that this association is stronger if the locomotor task is more challenging (e.g., obstacle course) and/or if the normal gait pattern is already altered (e.g., in patient populations). The results of the InChianti and other studies suggest that the reliance on EF increases as the locomotor task becomes more difficult and challenging. Still, many questions remain about these relationships. For example, while there is some evidence suggesting that a decline in EF ability may actually contribute to alterations in walking abilities, cause and effect has not been definitively demonstrated. In addition, most studies correlated only selected parameters of gait (e.g., speed or gait variability) with selected features of EF. Although associations were observed, the inclusion of a wider array of measures may provide a broader picture of the interdependence between gait and EF and

may help to define if and how specific EF properties affect specific aspects of walking.

ATTENTION

Definition of Attention

Attention may be considered a specific example of EF.^{7,32} The term covers a "number of different processes that are related aspects of how the organism becomes receptive to stimuli and how it may begin processing incoming or attended-to excitation, whether internal or external."⁵ There is, however, "no single and clear-cut definition of attention."⁵ Posner et al. view attention as an anatomical network whose "primary purpose is to influence the operation of other brain networks."³³ Attention can be classified into separate functions, including focused or selective, sustained, divided and alternating, although these distinctions are somewhat artificial. Selective attention, which enables filtering of stimulus information³⁴ and suppression of distractors, is commonly referred to as "concentration."⁵ Sustained attention refers to the ability to maintain attention to a task over a period of time.^{5,34} Divided attention refers to the ability to carry out more than one task at the same time and alternating attention refers to rapid shifting of attention from one task to another.^{5,34} Here we focus primarily on divided attention. This type of attention plays an important role in walking in multitasking and changing situations, serves as a common tool for examining the attentional demands of various tasks, including walking, and has clinical implications for fall risk.

Models of Dual Tasking

During the past 2 decades, many studies have investigated whether gait requires attention. Dual tasking is the most popular method for testing this question. This involves challenging attentional capacities, specifically the ability to divide attention. A priori, if gait is automatic and does not require attention, then simultaneous execution of an additional task should not affect gait or the performance of the other task. Before we review the studies that provide evidence that gait is indeed an attention-demanding, high-level, controlled task, we first briefly summarize the neuropsychology theories that have been proposed to explain why there are dual tasking costs in other situations.

Difficulties in the simultaneous performance of two or more tasks have led to the development of several neuropsychological theories on human information processing. Explanations generally revolve around the capacity-sharing theory, the bottleneck theory or the multiple resource models theory. The capacity-sharing theory

posits that attentional resources are limited in capacity, and so the performance of two attention-demanding tasks will cause deterioration of at least one of the tasks. When the time between the presentation of two or more stimuli is reduced, the time of processing will be increased because of the limitations of the shared capacity.³⁵ This theory assumes that it is possible to voluntarily allocate capacity to a specific task, even when both tasks are over-learned and largely automatic. Thus, the performance of an additional task during walking alters gait (e.g., stability, speed) or the execution of the second task or both. The bottleneck theory proposes that if two tasks are processed by the same neural processor or networks, a bottleneck is created in the processing of information. The processing of the second task will be delayed until the processor is free from processing the first task. This explains delays in the reaction times of the second task as a function of the temporal gap in the presentation of the two stimuli. Some investigators suggest that a delay may occur only at the stage of response selection, whereas others postulate that delay in processing can occur at any stage.^{35,36} According to this theory, performance of another task during walking might result in a slowed gait or delayed performance of the second cognitive task, but only if the neural networks involved in the two processes overlap.

The multiple resource models suggest that processing may need a number of resources.³⁷⁻³⁹ One of these theories claims that if two tasks do not share common resources, dual task interference will not occur. For example, walking while performing a cognitive task might not cause any changes, but a second motor task which shares the same resources as walking will. Conversely, the cross-talk theory posits that if both tasks are from a similar domain and use the same neuronal populations, they will not disturb each other.³⁷⁻³⁹ Neuroimaging investigations (e.g., PET, fMRI) have shown that during dual tasking activity is found in the anterior cingulate cortex and prefrontal areas, including the inferior frontal gyrus (which is not surprising, since activity of these area is attributed to EF).⁴⁰⁻⁴⁵ Such studies have been interpreted to support all three models and at present, there is no consensus on the theory that best explains human information processing and dual tasking costs.

Dual Tasking Costs in Healthy Adults

The effects of dual tasking on gait have been studied in various populations, including healthy young and older adults, as well as in patients suffering from neurological disease (e.g., post stroke, brain injuries, idiopathic fallers, Parkinson's disease, and Alzheimer's disease). Supplementary Table 1 (available online at [\[www.interscience.wiley.com/jpages/0885-3185/suppmat\]\(http://www.interscience.wiley.com/jpages/0885-3185/suppmat\)\) summarizes those investigations that utilized dual tasking to assess gait in these populations. As seen in Supplementary Table 1, most studies of healthy adults report that the performance of a second task influences gait. Healthy young adults generally walked more slowly when they were asked to walk and perform another task. Even healthy children exhibit a slowing of gait during dual tasking.¹⁰¹ Among healthy adults, dual tasking often caused a decline in the performance of the second task and often a reduced gait speed, however, other aspects of gait generally remained intact \(e.g., gait variability\) in healthy adults. Those few studies that reported no effect on gait in young adults may have used only a low cognitive demand dual task or perhaps prioritization was explicitly given to gait. Either way, from Supplementary Table 2, it is clear that gait depends on attention even in healthy adults who have intact locomotor and cognitive function; the "dual task cost" is non-zero in healthy adults.](http://</p></div><div data-bbox=)

Dual Tasking Costs in Healthy Older Adults

With aging, structural changes of the brain occur, especially in the prefrontal areas, regions that have been associated with the EF and attentional systems.^{5,9,22,23} Therefore, it is not surprising that elderly subjects may show difficulties in dual tasking, in general, and when walking while performing another task, in particular.^{8,102-104} Woollacott and Shumway-Cook reviewed a large number of works published in the 1980s and 1990s on the relationship between attention and postural control in aging (as well as in neurological patients).¹⁰² Most studies tested the attentional demands for maintaining standing balance in a variety of challenging situations, but only a few examined the effects of attentional loading on gait in the elderly.^{46,47,105} These reports demonstrated that the performance of cognitive tasks while walking may increase the reaction times of the cognitive task or reduce gait speed, but other changes in the gait pattern were not observed. More recent studies support these earlier findings that both healthy young adults and healthy older adults walk more slowly when they simultaneously perform a cognitive task (see Supplementary Table 2). In addition, although there may be some deterioration in the performance of the cognitive task that tends to increase with aging, gait stability (as measured by gait variability) is generally not affected by dual tasking.^{14,50,52,53,56,106} Other reports, however, showed that even healthy elderly people might show signs of gait instability under dual tasking conditions. For example, Dubost et al. reported increased gait variability in healthy older adults who performed simple arithmeti-

cal tasks⁶² and Lindenberger et al. demonstrated that the dual task costs increased with aging, especially when walking through a complex course (i.e., reduction in gait speed, increased number of missteps when walking over a narrow route, as well as reduction in performance of the cognitive task).⁴⁹ Thus, while there are a few exceptions, most studies in healthy older adults observe some “normal” strategies in response to dual tasking (e.g., reducing gait speed or decreasing the reaction time of the secondary cognitive task) without widespread changes to the gait pattern.

Dual Tasking Costs in Patients With Neurological Disease

Neurological patients have an especially difficult time walking while performing another task (see Supplementary Table 2). Typically, the dual tasking costs are larger than those seen in healthy, age-matched groups. This is likely due to a combination of factors. Most of the patient groups studied (e.g., post-stroke, Parkinson’s disease, and Alzheimer’s disease) have known deficits in EF and the ability to divide attention.^{20,107-111} At the same time, these patients also have an altered, less automatic walking pattern.^{75,112-115} For example, Parkinson’s disease is characterized by gait impairments and loss of walking automaticity^{116,117} that are accompanied by cognitive impairments of EF and attention.¹¹¹ As such, the effect of a cognitive challenge (attentional load) is easy to demonstrate: when attention resources of patients with Parkinson’s disease are allocated to more than one task, gait abnormalities increase. This is manifest as a slower gait speed, shorter strides, increased double support time, and increased stride-to-stride variability (see, for example, Fig. 2).^{15,75-77,79,80,83} Similar findings are found in idiopathic fallers, Alzheimer’s disease, post stroke, and in patients with head injuries (Supplementary Table 2). During dual tasking, the gait of these patient groups suffers from a compounding of effects: cognitive and motor deficits challenge the locomotor system’s ability to walk and carry out another task.

From this perspective, it’s understandable why dual task walking abilities may be able to reveal deficits not seen during single task walking and why dual tasking performance may be an especially sensitive predictor of fall risk. Dual tasking apparently increases the risk of falling among the frail elderly or those elderly who suffer from recurrent falls without any known organic reason (sometimes referred to as “idiopathic fallers”).¹⁴ In an elegant and very simple study, Lundin-Olsson et al. showed that older adults who could not “walk and talk” subsequently fell, while those subjects who could walk and talk were much less prone to future falls.⁶⁹ A few

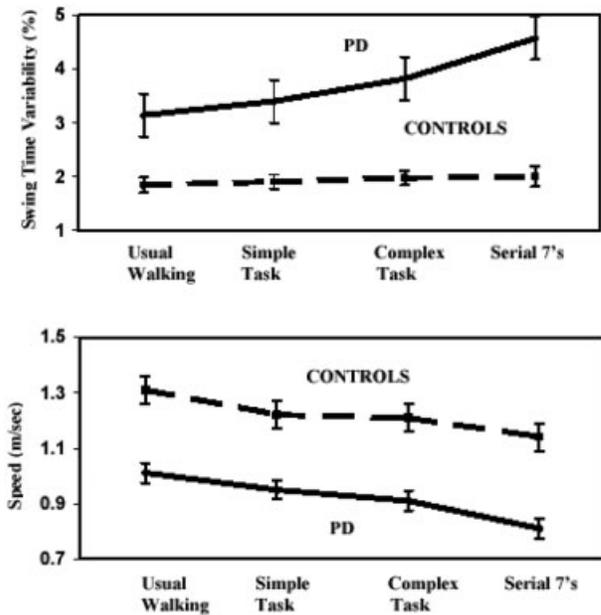


FIG. 2. Common and distinct effects of secondary, dual tasks on the gait of patients with Parkinson’s disease and age-matched healthy controls. Above: Swing time variability and Below: Average gait speed. While all both groups slowed down during dual tasking, gait variability increased only in the patient group. From Yogev et al.¹⁵

studies have found that dual tasking does not provide independent fall prediction information,^{57,91} perhaps because other factors also play a role (e.g., depression), however, several other investigations have also demonstrated that dual tasking severely affected gait parameters associated with fall risk in populations prone to falls, much more than in a healthy elderly cohort.^{14,51,71,72,118,119} For example, Springer et al. reported that idiopathic fallers increase their gait variability when performing a cognitive task while walking, while a control group comprised of non-fallers did not.¹⁴ Interestingly, this dual task cost was associated with poor performance in neuropsychological tests of attention and EF. In a study of 377 older adults, Faulkner et al. observed that dual tasking performance, both gait speed and the reaction time, were associated with fall risk.⁶⁵ Extrapolation from these findings suggests that to minimize fall risk in high-risk older adults, performance of other tasks should probably be minimized during walking.

Although there are differences in the dual tasks employed and the observed response, the clear message from Supplementary Tables 1 and 2 is that gait uses attention, even in healthy adults, and, further, that the dual task costs generally increase as gait becomes less automatic, e.g., in patient populations.

Prioritization: Competition Between Motor and Cognitive Demands

Simultaneous performance of two attention-demanding tasks not only causes a competition for attention, it also challenges the brain to prioritize the two tasks. Two areas of the brain are commonly mentioned in connection with the process of prioritization, the prefrontal cortex (PFC) and the anterior cingulate cortex (ACC). Activation of both of these areas has been well-documented when subjects perform dual tasking.^{40,41} Williams suggests that the significance and relevance of concurrent information is determined by a core motivation to minimize danger and maximize pleasure.¹²⁰ In agreement with this view, Bloem et al. reported that healthy young adults and, to a certain degree, healthy elderly give priority to the stability of gait when walking and performing a cognitive task.⁵¹ The unconscious, healthy “posture first” strategy might be one of the keys to avoiding hazards and preventing falls while walking. Consistent with this idea, when healthy adults performed a cognitive task while walking, quality of the task declined, but the gait pattern and gait stability did not, perhaps to avoid falling.^{49,56,106} Similarly, Grabiner and Troy proposed that the decrease in step width variability observed in young healthy adults who performed a second task while walking reflects an increase in dynamic gait stability.⁶⁰

These examples of appropriate prioritization of gait in healthy adults may be contrasted to the response to dual tasking in patient populations. Patients with Parkinson’s disease inappropriately use a “posture second” strategy and unnecessarily exacerbate their risk of falling in dual tasking situations.⁷⁸ Similarly, improper prioritization may partially explain why certain patients post-stroke are unable to follow a straight walking path.¹²¹ Further, older adults with an increased risk of falling apparently prioritize the planning of future stepping actions over the accurate execution of ongoing movements, a decision strategy that contributes to an increased likelihood of falls.¹²² In addition, one prospective study found that compared with non-fallers, elderly fallers did better on a simple arithmetic task during walking,⁶⁶ perhaps because they inappropriately used a “posture second” strategy. In a sense, fall risk may be exacerbated by intrinsic motor impairment, a decline in EF and in the ability to divide attention, as well as inappropriate utilization of limited resources.

All these examples, however, refer to situations, in which the subjects are not given any specific instructions regarding prioritization. In studies where the subjects were explicitly instructed to direct their attention to ei-

ther gait or to the cognitive task, the overt prioritization resulted in a reduced dual task decrement for the prioritized task.^{68,81} The potential effects of interventions based on changing prioritization are discussed later.

Comments on Methodology

The application of dual tasking to evaluate the role of attention during walking is generally well-accepted. Nonetheless, specific implementation issues are not yet standardized. Some studies explicitly prioritize one task over the other, whereas many do not explicitly instruct the subject.¹²³ The choice of the second task used to evaluate the effects of dual tasks on walking also varies widely between studies and there is no consensus on which one is most appropriate and which optimally creates attentional loading. Many of the tasks used are borrowed from neuropsychological tests, such as the verbal fluency task or the Stroop test, whereas others have been created by the authors of a specific study. A method for quantifying the level of attention loading is also lacking. This makes it difficult to compare results across studies.

Some considerations should be taken into account when choosing a task. The task should be difficult enough to load the attentional system, but it should not cause undue stress or anxiety. Another concern is the individual’s ability to perform the dual task. Tasks that require mathematical skills (such as serial 7 subtractions) might create only minimal loading of attention if the subject is highly skilled with mathematical calculations whereas subjects who are not comfortable with such tasks might be severely affected by the performance of such a task. Similarly, a test of verbal fluency might be relatively difficult, causing severe attention loading, in a subject with language difficulties. One way to take into account these individual differences is to adjust the dual task performance relative to single task ability. The degree to which the loading of attention remains constant throughout the assessment of the dual task effect on gait should also be considered. Naming of words that start with a given letter may be relatively easy initially, but more difficult as the test progresses. On the other hand, assuming the subject has sufficient practice, the attention devoted to serial subtractions is not likely to change over time during a given test. When assessing the consistency of gait over time (e.g. variability and related measures), the consistency of the attention loading of the additional task should also be taken into account.

CLINICAL IMPLICATIONS

Assessment of EF and dual tasking abilities can provide the clinician with important information about gait

TABLE 2. *Relatively simple tests of executive function that can be used at the bedside and in the clinic*

Test name	Brief description of test	Time to complete	Correlations with other tests
Frontal Assessment Battery (FABS) ¹³⁰	Six aspects of EF considered to relate to frontal lobe function are tested using a simple battery: conceptualization, mental flexibility, motor programming, sensitivity to interference, and inhibitory control	10 min	Wisconsin card sorting test ($r = 0.77$) Mattis Dementia Rating Scale ($r = 0.82$)
The Executive Interview (EXIT25) ¹³¹	Bedside assessment of executive cognitive impairment that includes 25 items. Cut off point of 15 of 50 discriminates non-demented elderly controls from subjects with cortical and non-cortical dementia	10 min	MMSE ($r = -0.85$) TMT part A ($r = 0.73$) TMT part B ($r = 0.64$) Test of sustained attention and tracking ($r = 0.83$)
CLOX: an executive clock drawing task ¹³²	This test discriminates between executive elements and non-executive elements of the task (free drawing vs. copying a clock). The authors suggest that clock drawing demands EF such as planning and abstract thinking. While CLOX does not evaluate specific EF components; it provides an overview of executive control	A few min	EXIT25 ($r = 0.83$) MMSE ($r = 0.85$)

EF, executive function; MMSE, mini mental state exam; TMT, trails making test.

disturbances and the risk of falling that might not be seen during a routine exam. Traditional, comprehensive neuropsychological testing of multiple cognitive domains typically takes many hours. More recently, computer-based tests have been developed to more quickly quantify reaction time and other features not typically evaluated using pen and paper tests.¹²⁴⁻¹²⁹ Still, for practical purposes, it would be desirable to obtain an initial evaluation of such abilities without submitting the patient to exhaustive and time consuming test batteries that may also demand special equipment. Tables 2 and 3 summarize simple and quick assessment tools that can be used to evaluate EF at the bedside or in the clinic and tasks

that can be used for dual tasking when directly assessing the effect on walking in such settings. These evaluations do not require special equipment, forms or extensive training of the examiner. Experience using these tests can give the clinician valuable insight into the degree to which the patient walks safely while encountering common everyday “dual tasks” and may assist in the prescription of therapeutic interventions and clinical recommendations about how to handle such situations. If deficits are suspected, more comprehensive testing may be appropriate. It is important to note, however, that these tests were not initially designed to assess EF in healthy elderly. For example, the CLOX was developed

TABLE 3. *Tasks that can be used to assess the effect of dual tasking on gait in the clinical setting*

Task	Description of task	Outcome measures	Limitations of task
Stops walking while talking ⁶⁹	Subject walks while conducting a conversation with the examiner (for example, answering questions regarding one’s medical history)	Walking speed Number of stops (walking)	No standardized of questions. Examiner should be consistent with the questions and level of question difficulty; ceiling effect
Arithmetic task (digit span, backward counting, serial 3 or 7 subtractions) ^{14,15,59,85}	Subject walks while counting back from 100 (or any other number), or subtracting 3’s or 7’s	Walking speed Number of stops Mistakes in calculations Number of calculations completed	Skill dependent: might be more difficult for some subjects than others
Carrying a tray with filled glasses of water ^{77,81,82,96}	Subject walks while holding a tray with at least one filled glass of water	Walking speed Number of stops Amount of water spilled	Involvement of upper extremities might affect the gait pattern Difficulty is dependent on the amount of water in the glasses; ceiling effect
Verbal fluency ^{57,62,67,71,76}	Subject walks while naming items that start with a certain letter or have a certain common characteristic (e.g., farm animals)	Walking speed Numbers of words generated	1. Skill dependent-might be more difficult for some subjects than others 2. Subjects may generate most words in the initial part of the test

for studying patients with Alzheimer's disease and the FABS was developed for evaluating patients with frontal lobe dysfunction. There is still work to be done in developing appropriate assessment tools for healthier subjects.

Possible Treatments

Treatment of an impaired ability to simultaneously perform another task while walking could greatly enhance quality of life and reduce the risk of falling. The dual tasking effects on walking are especially increased among patient populations who have gait impairment due to both motor and cognitive deficits. It follows, therefore, that treatment designed to reduce the dual tasking costs during walking should focus on one or both of these domains. Several potential strategies emerge.

Although there are changes in motor learning capabilities in older adults and in patients with neurological disease, the capacity to learn or relearn motor tasks remains largely intact.¹³³⁻¹³⁵ Thus, theoretically, training of dual tasking abilities should also be feasible. This possibility has been examined in several neuropsychological studies.^{136,137} Two main strategies emerge in that context: the part-task strategy involves training each task separately while the whole-task strategy involves simultaneous training of both components of the dual task. Although the findings are somewhat controversial, dual tasks were found to be more than the sum of their parts and there appears to be added benefits to training of both tasks at the same time.¹³⁶ Furthermore, training dual tasking as a whole task was apparently critical for acquiring attentional control and task coordination strategies.¹³⁶ Consistent with this, an fMRI study found reduced activation of areas that were initially involved with dual tasking processing after whole-task training, interpreted as an "increase in neural efficiency."^{5,138}

The possibility of improving gait while performing dual tasks using the whole-task or part-task strategies has not been well-studied. There is some evidence demonstrating that the dual tasking effects on postural control can be reduced with dual task training^{93,139,140} and one can extrapolate that similar effects should also be achievable for walking. Pilot data also support this idea.^{74,141} For example, Toulotte et al. trained 8 elderly non-faller and 8 elderly fallers twice weekly for 3 months.⁷⁴ Training included single and dual task exercises aimed to improve static and dynamic balance. Significant improvements in balance (e.g., unipedal stance time) and gait speed were observed in both groups in both single and dual task conditions. Another possibility is to train to alter inappropriate prioritization.⁶⁸ Strong evidence is currently lacking and many questions remain about effi-

cacy and the design of optimal interventions to improve dual tasking during walking.

An alternative strategy focuses on improving cognitive function. There is some evidence suggesting that interventions designed to improve cognitive function in older adults and in patient populations achieve their goals and carryover to functional domains. For example, behavioral interventions and computer "games" improve cognitive function, including attention and EF, in older adults and in patients with Parkinson's disease.^{133,142-145} While the impact of such gains on gait has yet to be investigated, transfer to other everyday tasks (e.g., instrumental activities of daily¹⁴⁵) is apparently successful.

Pharmacological therapy may be another way of affecting gait via the "cognitive" channel. A randomized-controlled study of gait in children with ADHD found that methylphenidate, the most widely used treatment option for patients with ADHD, reduced the dual task costs.¹⁰¹ Studies in patients with Parkinson's disease demonstrated that methylphenidate also improves EF, walking times, and gait speed while reducing gait variability^{146,147} and similar findings have been observed in older adults.¹⁴⁸ The precise mechanisms whereby these improvements were achieved remain to be more firmly established. One possibility is that MPH inhibits presynaptic dopamine reuptake and also inhibits the presynaptic norepinephrine transporter.¹⁴⁷ There is, however, evidence suggesting that these findings result from the influence of the drug on cognitive function, and not a general "motor" or stimulant effect.¹⁴⁶ Some suggest that dopamine plays a key role in the attentional behavior and that the mesocortical dopaminergic system is essential for the function of the DLPFC,^{149,150} presumably the anatomical substrate of EF processes. Animal studies support the idea that optimal levels of dopamine contribute to the focus of attention. Therefore the effect of MPH on dopamine could be critical both to motor and cognitive processes.¹⁵⁰ While there appears to be much potential for reducing dual tasking costs, all of the therapeutic options described have yet to be investigated fully and efficacy remains to be demonstrated in large scale controlled studies.

Perspectives and Conclusions

In this review, we have seen that a substantial body of evidence indicates that gait, even in healthy young adults, utilizes attention (recall Supplementary Table 1). From this perspective and understanding, it becomes easier to interpret somewhat surprising findings of recent epidemiological studies, link walking and dementia, in two directions. Several large scale, longitudinal studies have demonstrated that subjects with gait abnormalities

at baseline had a significantly increased risk of developing dementia as much as 6 to 10 years later¹⁵¹⁻¹⁵⁴; in other words, subtle gait changes predicted the subsequent development of dementia. At the same time, results from four prospective longitudinal studies, sampling thousands of elderly subjects during a similar 6 to 10 year follow-up, suggest that people who walk daily have a significantly reduced risk of developing dementia compared with those who do not walk or walk infrequently.¹⁵⁵⁻¹⁵⁸ While the relationship between walking and cognitive function is clearly multifactorial, all of these findings can be readily explained if gait makes use of and exercises EF and attention. It is possible that gait changes predict the development of dementia in part because gait depends on and is marker of EF and daily walking prevents the development of dementia because it makes use of EF (“use it or lose it”). Support for this view would be strengthened by longitudinal studies of the relationship between dual tasking gait abilities and the development of dementia, but the results from such reports are not yet available.

Recent studies have established the fact that attention demanding tasks change the walking pattern in all subjects, to some degree, and that alterations in EF, in particular attention, are associated with gait disturbances. A causal relationship between EF changes and gait changes remains to be more firmly proven, however, there is ample evidence demonstrating a relationship between these two seemingly disparate domains, including numerous investigations, which have documented changes in the gait pattern in response to dual tasking. This dependence is most notable in patient populations where the ability to compensate for an impaired gait is restricted due to a lack of “cognitive reserve.” To more fully evaluate gait abnormalities and fall risk, assessment of the EF and dual tasking walking abilities should, perhaps, become a part of the routine examination among neurological patients who suffer from a “double hit” on key functions that contribute to gait. Further work is needed to establish treatment options. Nonetheless, it seems likely that interventions that target cognitive function and those that train the ability to walk and perform another task may be successful at enhancing gait and reducing the dual tasking costs that impact on functional abilities and fall risk in many patient populations.

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