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Dual tasking, gait rhythmicity, and Parkinson's disease: Which aspects of gait are attention demanding?

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Abstract

Cognitive function and the performance of a secondary, dual task may affect certain aspects of gait, but the relationships between cognitive function and gait are not well understood. To better understand the motor control of gait and the relationship between cognitive function and gait, we studied cognitive function and the effects of different types of dual tasking on the gait of patients with Parkinson's disease (PD) and controls, contrasting measures of gait automaticity and rhythmicity with other features. Patients with idiopathic PD ($n = 30$; mean age 71.8 year) with moderate disease severity (Hoehn and Yahr Stage 2–3) were compared to age and gender-matched healthy controls ($n = 28$). Memory and executive function were also assessed. In both groups, gait speed decreased in response to dual tasking, in a parallel fashion. For the PD group only, gait variability increased compared to usual walking. Executive function was significantly worse in the PD group, while memory was not different in the two groups. Executive function measures were significantly correlated with gait variability during dual tasking, but not during usual walking. These findings demonstrate that regulation of gait variability and rhythmicity is apparently an automatic process that does not demand attention in healthy adults. In patients with PD, however, this ability becomes attention-demanding and worsens when subjects perform secondary tasks. Moreover, the associations between executive function and gait variability suggest that a decline in executive function in PD may exacerbate the effects of dual tasking on gait, potentially increasing fall risk.

Introduction

A growing body of evidence links postural control and gait to cognitive function (Marquis *et al*., 2002; Verghese *et al*., 2002b; Hausdorff *et al*., 2005) and suggests that even in healthy young subjects, these processes are not quite automatic, but consume some amount of attentional resources (Camicioli *et al*., 1997; Brauer *et al*., 2002; Woollacott & Shumway-Cook, 2002). Dual tasking paradigms have been used to study this dependence. If attentional resources are limited in capacity and if both gait and a secondary task are attention demanding, performance of at least one of the tasks will deteriorate when they are performed simultaneously. In general, dual tasking relies upon executive function and the ability to divide attention (Della *et al*., 1995). Neuroimaging investigations of different dual tasking modalities have found common activity of the dorsolateral prefrontal cortex and anterior cingulate cortex, highlighting the role of higher-level cognitive and frontal lobe function (Szameitat *et al*., 2002). These cognitive functions are generally impaired in Parkinson's disease (PD) (Brown & Marsden, 1991; Uekermann *et al*., 2004), but only a small number of studies have investigated the effects of dual tasking on gait in patients with PD (Morris *et al*., 1996; Camicioli *et al*., 1998; Bloem *et al*., 2000; O'Shea *et al*., 2002; Hausdorff *et al*., 2003) and, more generally, it is not clear which aspects of gait are sensitive to dual tasking or why.

In PD, alterations in walking, including reduced gait speed, shortened stride, reduced swing times, and decreased arm swing, are common (Morris *et al*., 1994; Morris *et al*., 1996; Ebersbach *et al*., 1999; Morris *et al*., 2001a). Increased stride-to-stride variability, a marker of arrhythmicity and reduced automaticity related to gait unsteadiness and fall risk, is also typically observed in patients with PD (Blin *et al*., 1990; Blin *et al*., 1991; Hausdorff *et al*., 1998; Hausdorff *et al*., 2000; Schaafsma *et al*., 2003; Frenkel-Toledo *et al*., 2005). To achieve a more normal gait, PD patients may recruit attentional resources to compensate for the damaged automaticity (Morris *et al*., 1996; Rubenstein *et al*., 2002). This ability to circumvent the impaired basal ganglia using cortical inputs is, however, limited because it may require higher-level cognitive function. As noted, executive function and attention are also diminished in PD (Brown & Marsden, 1991; Rowe *et al*., 2002; Uekermann *et al*., 2004). The relationships between the changes in gait and cognitive function, their response to dual tasking, and their influence on fall risk in PD are, however, not well understood (Bloem *et al*., 2000). The purposes of the present study were, therefore to: (i) determine how dual tasking affects gait in PD; (ii) compare the effects of different types of dual tasks on gait and (iii) evaluate the relationship between specific cognitive domains and gait changes in PD. Therefore, with a focus on measures of automaticity and rhythmicity, we studied the effects of different types of dual

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tasking on the gait of patients with PD and controls and the relationship between cognitive function and gait.

Materials and methods

Subjects

Thirty patients with idiopathic PD, as defined by the UK Brain Bank criteria (Gelb *et al*., 1999), were recruited from the outpatient clinic of the Movement Disorders Unit at the Tel-Aviv Sourasky Medical Center. Patients were invited to participate if their disease stage was 2–3 on the Hoehn and Yahr scale (Hoehn & Yahr, 1967), they were taking antiparkinsonian medications, they did not experience motor response fluctuations, they were able to ambulate independently, they did not have dementia [as determined by DSM IV criteria and scores on the Mini-Mental State Exam (MMSE)], and they were between 60 and 90 years of age. Subjects were excluded if they had clinically significant musculo-skeletal disease, cardio-vascular disease, respiratory disease, other neurological disease, major depression, or uncorrected visual disturbances. We did not explicitly exclude patients who took sedatives, a potential confounder, but note that aside from one patient who took a small dose of alprazolam (0.5 mg × 2 a day), none of the patients were taking sedatives. Consecutive patients who met the inclusion and exclusion criteria were studied. The PD patients were compared to 28 healthy control subjects of similar age. Controls were recruited from several sources in the community, i.e. patient's spouses, local senior centres, and volunteers from the community; it was a 'convenient' sample. Control subjects fulfilled the same inclusion and exclusion criteria as the patients with PD and did not have an extrapyramidal syndrome, based on neurological examination. The sample size was estimated based on a previous pilot study (Hausdorff *et al*., 2003). The study was approved by the Human Studies Committee of Tel-Aviv Sourasky Medical Center. All subjects gave their written informed consent according to the declaration of Helsinki, prior to entering the study.

The study population was characterized with respect to age, gender, height, weight, Mini-Mental State Exam (MMSE) scores (Folstein *et al*., 1975; a gross measure of cognitive function widely used to screen for dementia), the Timed Up and Go test (TUG; a gross measure of balance and lower extremity function; Mathias *et al*., 1986; Okumiya *et al*., 1998; Shumway-Cook *et al*., 2000; Morris *et al*., 2001b), and the Berg Balance Scale (Berg *et al*., 1995). Subjects were also asked about their history of falls in the past six months. The Unified Parkinson's Disease Rating Scale (UPDRS; Fahn *et al*., 1987) was used to quantify disease severity and extra-pyramidal signs.

Cognitive assessment

A computerized cognitive assessment system, Mindstreams® (NeuroTrax Corp., NY), was used to evaluate specific domains of cognitive function (Dwolatzky *et al*., 2003; Schweiger *et al*., 2003). We measured executive function using the Stroop and Go–NoGo tests, two widely used tests of executive function, and memory, which was used here as a control to see if any observed deficits were global or specific to executive function. The Stroop paradigm 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 perceptual set to conform to changing demands and suppress a habitual response in favour of an unusual one (Spreen & Strauss, 1988; MacLeod, 1991). The Go–NoGo test provides a complimentary measure of executive function and response inhibition. For both of these tests, we evaluated accuracy, reaction time, and a composite score (100*accuracy/reaction time) that takes into account speed-accuracy trade-offs. Verbal and nonverbal memory was also assessed using tests that do not incorporate timing measurements and generally do not stress executive function. Briefly, ten pairs of words (or pictures) 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 min. 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 and, as expected that these measures of memory are decreased in persons with dementia and mild cognitive impairment (Dwolatzky *et al*., 2003; Schweiger *et al*., 2003).

Dual tasks

The effects of dual tasking on gait were examined under four conditions: (i) baseline (usual walking with no dual task); (ii) simple task; (iii) complex task and (iv) arithmetic task. During the baseline condition, subjects walked at a comfortable pace without any secondary task in a well-lit, obstacle free, 25-m long, 2-m wide corridor. During the simple task, subjects walked while listening through ear phones to a text on tape, knowing that they would be asked to answer ten questions regarding the content of the text after the walk. All subjects also performed the simple test while sitting, before all tests of walking (using a different text than the one they listened to while walking). During the complex task, subjects walked while listening through ear phones to a different text on tape, as in the simple task. In addition, subjects were asked to count how many times two predefined words appeared in the text. This kind of attention-demanding task is called 'phoneme monitoring' and is often used as a distractor in neuropsychological research (Tseng *et al*., 1993). During the arithmetic task, subjects walked while performing serial 7 subtractions out loud, starting from 500.

Walking protocol

Subjects were instructed to walk at their normal pace on level ground, for 2 min under each of four conditions (usual walking and three dual-tasking conditions). The instructions for the dual-task conditions were to walk at a comfortable pace and to perform the secondary task. No instruction for priority of one of the tasks (walking vs. cognitive task) was given. The order of the tasks was simple task, complex task, walking without a secondary task (baseline), and finally, walking while subtracting serial 7s. Performance on the simple task was evaluated by counting the number of mistakes that were made using a multiple choice test of ten questions on the content of the text. On the complex task, performance was evaluated both by counting the number of mistakes on the multiple choice test of content and by evaluating performance on the phoneme monitoring (the percentage of mistakes made when counting the predefined words). Evaluation of performance on the serial 7 subtractions included the total number that subjects calculated and the number of mistakes they made during the calculation.

Gait assessment

A previously described computerized system was used to quantify gait rhythm, the timing of the gait cycle (i.e. the stride time), swing time, and stride-to-stride variability (Bazner *et al*., 2000; Frenkel-Toledo *et al*., 2005). The system measures the forces underneath the foot as a function of time. The system consists of a pair of shoes and a recording unit. Each shoe contains eight load sensors that cover the surface of the sole and measure the vertical forces under the foot. The recording unit ($19 \times 14 \times 4.5$ cm; 1.5 kg) is carried on the waist. Plantar pressures under each foot are recorded at a rate of 100 Hz. Measurements are stored in a memory card during the walk, and, after the walk, they are transferred to a personal computer for further analysis. The following gait parameters were determined from the force record using previously described methods (Hausdorff *et al*., 2000; Hausdorff *et al*., 2001; Hausdorff *et al*., 2003; Schaafsma *et al*., 2003; Frenkel-Toledo *et al*., 2005): average stride time, swing time (%), stride time variability, and swing time variability. Variability measures were quantified using the coefficient of variation, e.g. stride time variability $= 100 \times$ (standard deviation/average stride time). Average gait speed was determined by measuring the average time the subject walked the middle 8 m of the 20-m walk during the two minutes of testing.

All assessments were made in the same day. The testing session was divided into two parts. In the first part of the session, the clinical exam and questionnaires, the Mini Mental State Exam, the Timed Up and Go, the Unified Parkinson's Disease Rating Scale, the Berg Balance Scale, and cognitive assessment were administered. After a rest break, gait and the effects of dual tasking were assessed.

Statistical analysis

Descriptive statistics are reported as mean ± SD. We used the Student's-*t* and chi-square tests to compare the PD and control subjects with respect to different background characteristics (e.g. age, gender) and with respective to cognitive function. In order to estimate the effect of the secondary tasks on gait, we applied mixed effect models for repeated measures to evaluate within group and between group differences. The model does not assume equal variance between patients and controls. For each gait variable, we applied a separate model where the dependent variable was the gait measure (a continuous one) and the independent variables were categorical: the group (PD patients, controls) and the secondary task (none, simple task, complex task, serial 7 subtractions), and the group × secondary task condition interaction term. The fixed factors in these models were group and the secondary task while the subject was the random factor. In each model, for the secondary task, the 'none' category was considered as the reference category, inherent in the modelling procedure. *P*-values reported are based on two-sided comparison. A *P*-value equal to 0.05 was considered statistically significant. The FDR approach was used to check for any multitesting effect (there was none). All statistical analyses were performed using SAS 8.2 (Proc Mixed).

Results

Subject characteristics and baseline measures

Table 1 summarizes the demographics and clinical characteristics of the study population. Both groups were similar with respect to age, gender, height, weight and years of education. As expected, the subjects with PD scored higher (worse) on the UPDRS, performed worse on measures of balance and lower extremity function, and fell more often, compared to the controls. Among the PD patient group, seven subjects were in Hoehn and Yahr disease stage 3, eight were in disease stage 2.5, and 15 were in disease stage 2. Scores on the MMSE were slightly lower among the subjects with PD, but the mean for both groups was close to 30.0 (a perfect score). Consistent with previous findings, under usual walking conditions, all measures of gait except for the average stride time were significantly worse in the subjects with PD, compared to the control group.

Effects of dual tasking

Figure 1 shows an example of the effects of dual tasking on gait in a patient with PD and a control subject. Table 2 summarizes the effects in the two groups. In both groups, gait speed decreased significantly during the simple listening, complex listening and serial 7 tasks, compared to usual walking (in PD $P = 0.002$, $P = 0.0001$, $P = 0.0001$ and in controls $P = 0.0001$, $P = 0.0001$, $P = 0.0001$, respectively). A significant group × secondary task interaction was not observed ($P = 0.37$), indicating that the effects of dual task on gait speed were similar in both groups. The shared effect of dual tasking on gait speed can be seen in Fig. 2 (note the roughly parallel lines).

The effects of dual tasking on average stride time and average swing time were generally similar to those observed for gait speed. In both groups, the average stride time increased significantly in the simple listening, complex listening and serial 7 tasks, compared to usual walking (in PD $P = 0.038$, $P = 0.007$, $P < 0.001$ and in controls $P = 0.0014$, $P = 0.0011$, $P = 0.0001$, respectively). A significant group × secondary task interaction was not observed ($P = 0.11$) for average stride time, indicating that the effects of a secondary task on average stride time were similar in both groups. Like gait speed and average stride time, average swing time decreased significantly in both groups in the simple listening, complex listening and serial 7 tasks, compared to usual walking (in PD $P = 0.039$, $P < 0.001$, $P < 0.001$ and in controls $P = 0.031$, $P = 0.004$, $P = 0.001$, respectively). The effects of dual tasking on swing time tended to be larger in PD compared to controls and there was a significant group × secondary task interaction ($P = 0.0010$).

Whereas dual tasking influenced gait speed, average stride time and average swing time in both the subjects with PD and in the controls, dual tasking affected the variability of gait only in the subjects with PD (recall Fig. 1). Among the subjects with PD, stride time variability increased significantly during the serial 7 task ($P = 0.001$). In contrast, among the controls, dual tasking did not affect stride time variability ($P = 0.187$); stride time variability was similar under all four walking conditions. The group × secondary task interaction was not significant ($P = 0.15$). Similarly, in the subjects with PD, swing time variability increased significantly during the complex listening and serial 7 tasks, compared to usual walking ($P < 0.001$ in both cases). Among the controls, dual tasking did not affect swing time variability; swing time variability was similar under all four walking conditions. For swing time variability, a significant group × secondary task interaction was found ($P < 0.0001$), indicating that the effects of the secondary tasks were different in the two groups. This PD-specific response can be readily seen in Fig. 2.

Performance on secondary tasks

Table 3 summarizes the performance on the secondary, dual tasks. There was no significant difference between the groups on the listening tasks when subjects were tested during sitting, but there was a tendency

TABLE 1. Subject characteristics

	PD ($n = 30$)	Controls ($n = 28$)	P-value
General and disease			
Age (year)	70.9 ± 7.9	69.8 ± 6.3	0.509
Height (m)	1.68 ± 0.11	1.69 ± 0.07	0.893
Weight (kg)	73.9 ± 16.0	72.7 ± 12.5	0.628
Education (years)	13.9 ± 3.8	13.7 ± 2.1	0.914
MMSE	28.1 ± 1.6	29.1 ± 1.1	0.011
Hoehn and Yahr Stage	2.3 ± 0.4	–	–
UPDRS Total	32.5 ± 12.0	0.5 ± 0.9	< 0.001
UPDRS motor (Part III)	17.5 ± 8.3	0.5 ± 0.9	< 0.001
Balance and falls			
Timed Up and Go (s)	13.3 ± 5.7	8.1 ± 1.2	< 0.001
Berg Balance Scale	52.7 ± 2.9	55.3 ± 1.5	< 0.001
Subjects reporting falls (%) in past 6 months	46	0	< 0.001

Data are presented as mean ± SD or percentage, as indicated.

towards group differences when they were tested during walking. During the more complex listening task, both groups also performed similarly on tests of comprehension and recalled similar number of phonemes. There was, however, a significant difference between the groups in the percentage of mistakes subjects made during the serial 7 subtraction. Listening comprehension tended to decrease during walking compared to sitting in the patients with PD ($P = 0.095$), but not in the controls. In both groups, listening comprehension significantly decreased during complex listening (with phoneme monitoring) compared to simple listening ($P < 0.01$), suggesting that the complex listening task (during walking) was more difficult than the simple listening task (during walking). Note that under all conditions, scores demonstrate that the secondary task was not ignored and attention was devoted to perform these tasks, in both groups.

Cognitive function and dual tasking

As noted, the increase in variability in response to dual tasking was unique to the subjects with PD. We sought to determine whether a cognitive function measure might explain this dual tasking effect on gait variability. As summarized in Table 4, subjects with PD performed worse on tests of executive function, but not on tests of memory, compared to the controls. Among the measures of executive function, Go–NoGo performance (all measures) was not significantly correlated with stride time variability or swing time variability during the serial 7 subtractions ($P > 0.19$), but there were some associations during the complex walking task (e.g. $r = -0.30$; $P = 0.027$ between the composite index and stride time variability) when all subjects were pooled together. Stroop test performance (reaction time and composite score) was correlated with stride time variability and with swing time variability and this association became strongest while performing the serial 7 subtractions when both subject groups were pooled together (Table 5). Although not identical, similar trends were seen when only the PD subjects were examined. For example, the Stroop test composite index tended to be inversely correlated with usual walking stride time variability ($r = -0.38$; $P = 0.067$) and this association became tighter during the complex walking task ($r = -0.50$; $P = 0.006$).

Discussion

Consistent with previous studies, the results of the present investigation demonstrate that dual tasking and attention influence gait. Here

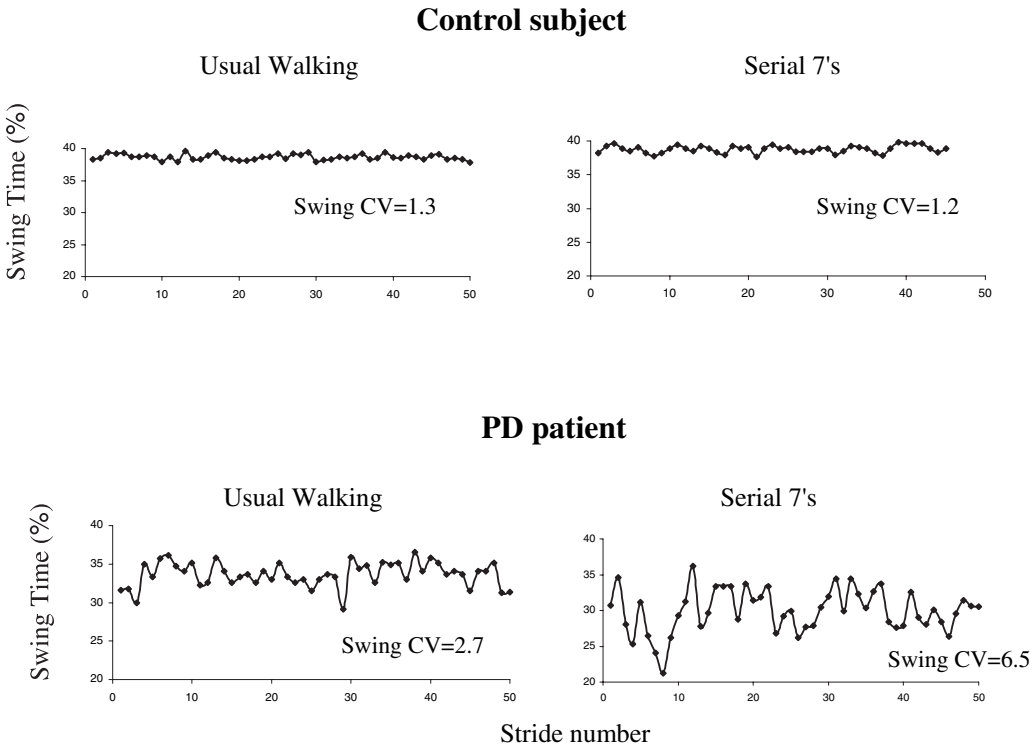

FIG. 1. Example of portion of swing time series from a patient with PD and a control subject, under usual walking conditions and when performing serial 7 subtractions. Under usual walking conditions, variability is larger in the patient with PD (coefficient of variation, CV = 2.7%), compared to the control subject (CV = 1.3%). Variability increases during dual tasking in the subject with PD (CV = 6.5%), but not in the control subject (CV = 1.2%).

TABLE 2. Effects of dual tasking on gait in PD and controls

	Dual tasking condition			
	Usual walking	Simple task	Complex task	Subtracting serial 7s
Gait speed (m/s)				
PD	1.05 ± 0.23)+	0.95 ± 0.27**	0.91 ± 0.27***	0.85 ± 0.27***
Controls	1.31 ± 0.19	1.22 ± 0.18***	1.21 ± 0.18***	1.19 ± 0.17***
Average stride time (s)				
PD	1.08 ± 0.15	1.12 ± 0.16*	1.12 ± 0.15**	1.16 ± 0.21***
Controls	1.07 ± 0.08	1.09 ± 0.09**	1.09 ± 0.08**	1.11 ± 0.10***
Stride time variability (%)				
PD	2.11 ± 0.73+	2.13 ± 0.71	2.23 ± 0.84	2.68 ± 1.07***
Controls	1.72 ± 0.46	1.61 ± 0.35	1.60 ± 0.42	1.90 ± 0.73
Swing time (%)				
PD	35.57 ± 2.44 +	34.64 ± 2.76*	34.10 ± 3.03***	33.27 ± 3.50***
Controls	38.03 ± 1.35	37.73 ± 1.41*	37.60 ± 1.62**	37.29 ± 1.97
Swing time variability (%)				
PD	2.76 ± 1.36 +	3.39 ± 1.64	3.82 ± 2.43**	4.29 ± 2.70***
Controls	1.86 ± 0.40	1.90 ± 0.53	1.97 ± 0.57	1.95 ± 0.57

*$P < 0.05$, **$P < 0.01$, ***$P = 0.001$ compared to usual walking (within group comparison) based on the Mixed Model approach. $^{+}P < 0.05$ comparing PD to controls during usual walking based on the Mixed Model approach.

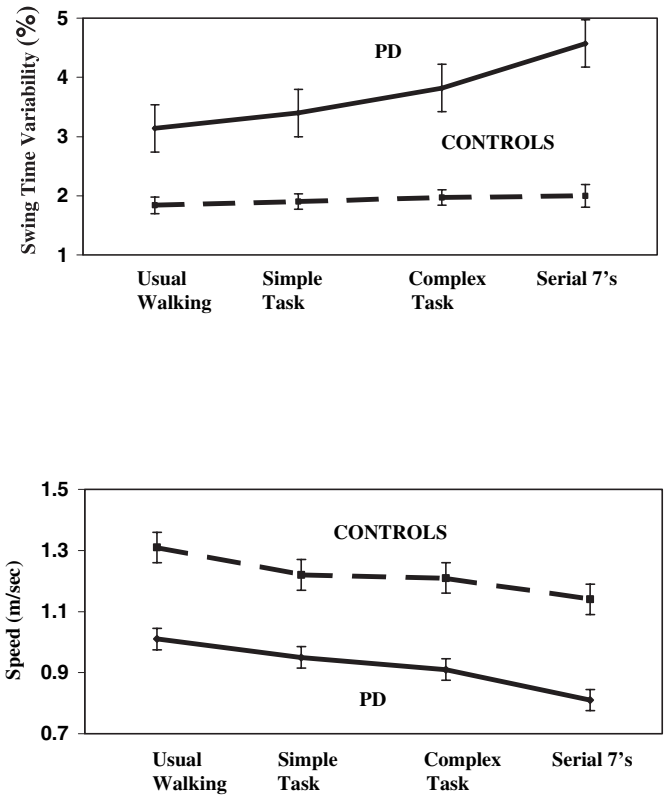

FIG. 2. Example of the common and distinct effects of secondary, dual tasks on the gait of patients with Parkinson's disease and controls. (Top) Swing time variability. (Bottom) Average gait speed.

we extend these studies in a number of important ways. (i) We find that dual tasking decreases gait speed, in both patients with PD and in healthy controls. (ii) In healthy older adults, gait automaticity and rhythmicity is robust; the performance of complex cognitive tasks has no effect on variability of the stride or swing time, even though it does affect gait speed. (iii) In contrast, in PD, dual tasking markedly increases gait arrhythmicity and unsteadiness (as seen in stride time and swing time variability). (iv) Interestingly, this increase in arrhythmicity among the patients with PD is seen with complex tasks that severely tax attention and involve other motor tasks such as articulation (i.e. serial 7 subtractions), but also with passive listening (recall Table 2). (v) The present results support the idea that executive function deficits in PD contribute to the dual tasking decrement in gait variability. As discussed below, these findings also provide insight into the physiology that connects gait and cognitive function and its changes with PD and further our understanding of the factors that predispose patients with PD to falls.

Disparate effects of dual tasks on gait speed and variability

The dual tasking effect on gait speed was similar in both groups, consistent with the results of O'Shea *et al*. (2002). On the other hand, gait variability (as reflected in both stride time variability and swing time variability) generally increased in response to all three dual tasks in the patients with PD, but not in the control group. This disparate response suggests that different mechanisms contribute to the regulation of gait variability and gait speed. Moreover, the present results indicate that a reduced gait speed in response to dual tasking is a normal, perhaps protective response. Apparently, the 'choice' of gait speed is related to cognitive loading conditions and other attentional demands. Dual tasking heightens deficits in automaticity and the ability to maintain a steady gait rhythm in PD, but not in healthy controls. These findings can be synthesized if one considers the regulation of gait rhythmicity and stride-to-stride variability as an automatic process under physiologic conditions, but as an attention-demanding task in PD.

In general, the two measures of variability, stride time and swing time variability, responded similarly to dual tasking in both groups. There were, however, some subtle differences. Gabell & Nayak (1984) speculated about these two measures of variability. They suggested that stride time variability is determined predominantly by the gait-pattering mechanism (repeated sequential contraction and relaxation of

TABLE 3. Performance on secondary tasks in PD and controls

Test condition	Test	PD ($n = 30$)	Controls ($n = 28$)	P-value (PD vs. Controls)
Sitting	Simple listening (number of mistakes)	2.6 ± 1.8	2.4 ± 1.7	0.727
Walking	Simple listening (number of mistakes)	3.7 ± 1.8	2.6 ± 1.3	0.053
Walking	Complex listening (number of mistakes)	4.6 ± 1.8	4.1 ± 1.1	0.243
Walking	Complex listening (mistakes in phoneme monitoring, %)	33 ± 0.2	26 ± 0.2	0.204
Walking	Serial 7s subtracted (number of counted items)	22.2 ± 11.9	29.5 ± 9.5	0.029
Walking	Serial 7s mistakes (number of mistakes)	4.9 ± 4.2	2.6 ± 4.7	0.149
Walking	Serial 7s composite score (mistakes in counting, %)	26% ± 0.2	11% ± 0.2	0.033

Data are presented as mean ± SD.

TABLE 4. Cognitive function in PD and controls

	PD ($n = 30$)	Controls ($n = 28$)	P-value
Executive function			
Stroop test accuracy (%)	62.4 ± 29.5	80.2 ± 32.2	0.036
Stroop test reaction time (ms)	976.7 ± 372.5	715.8 ± 318.2	0.007
Stroop test composite score	8.0 ± 5.9	13.2 ± 6.9	0.004
Go–NoGo accuracy (%)	91.1 ± 8.0	93.2 ± 6.5	0.282
Go–NoGo reaction time (ms)	542.0 ± 129.0	467.8 ± 76.3	0.010
Go–NoGo composite score	17.4 ± 4.0	20.3 ± 3.3	0.004
Memory			
First trial recall (%)	42.3 ± 23.1	56.1 ± 30.5	0.223
Fourth trial recall (%)	75.3 ± 34.4	77.5 ± 26.9	0.785
Average recall (%)	64.8 ± 24.6	68.5 ± 32.41	0.628
Delayed recall (after 10 min, %)	70.5 ± 27.9	71.0 ± 32.1	0.957

TABLE 5. Correlation between gait variability and Stroop test performance

	Stride time variability	P-value	Swing time variability	P-value
Usual walking	0.31	0.032	0.40	0.004
Complex listening	0.40	0.003	0.41	0.001
Subtracting serial 7s	0.47	0.006	0.49	0.004

Entries are Pearson's correlation coefficient (P-value) obtained when correlating stride time variability and swing time variability with Stroop test reaction time among all subjects. Similar results were obtained when the Stroop test composite index was used or when Spearman's correlation coefficients were examined.

muscle groups resulting in walking), whereas swing time (double support time) variability is determined predominantly by balance-control mechanisms. Perhaps this might explain the observed differences between these two measures, but further work is needed to better understand the small discrepancies between these two aspects of gait variability. It may be somewhat artificial to completely separate them along these lines as each are likely influenced by both balance and pacing mechanisms.

This impairment in the regulation of gait rhythmicity in patients with PD may be related to alterations in the ability to generate 'internal cues' in the SMA, a necessary step in the creation of a normal sequenced movement. Alternatively, Blin *et al*. (1990) suggested that the increased gait variability seen in PD might result from the deficits in the ability to generate adequate muscle strength. In contrast, Baltadjieva *et al*. (2004) found no difference between PD patients and controls in the variability of the vertical ground reaction force while walking, suggesting that the increased variability seen in PD is due to a central impairment and not due to variability of muscle force generation in the lower limbs. The present findings support the idea that central brain mechanisms influence gait rhythmicity in PD. Otherwise, why would dual tasking influence gait variability? It is unlikely that dual tasking affects the pyramidal system's ability to generate appropriate muscle strength and the same muscle forces are needed during usual walking and during dual task walking, yet gait variability increases significantly during dual tasking in PD.

In PD patients, once attention is shifted to secondary tasks away from walking, there is deterioration in one's ability to maintain rhythmicity and steadiness of gait. Even if one assumes that gait does consume some degree of attentional resources in healthy older adults, as suggested by other studies (Maylor & Wing, 1996; Lindenberger *et al*., 2000; Woollacott & Shumway-Cook, 2002) and the decrease in gait speed observed in the present study, healthy subjects can apparently attend to secondary cognitive tasks without influencing gait steadiness. It follows that control over the stride-to-stride consistency of gait normally requires minimal attention. Under healthy conditions, consistency of gait is maintained even when attention is taxed. However, in PD, consistency of gait is impaired, especially when attention needs to be shared.

Gait variability and risk of falling in patients with PD

Our findings raise the possibility that the increased gait variability during dual tasking might explain some of the high risk of falls seen in patients with PD. Falls are a major cause of injuries, hospitalization and dependence in PD (Ashburn *et al*., 2001a; Wood *et al*., 2002; Bloem *et al*., 2004). While it is apparent that certain features of PD increase fall risk, e.g. impaired postural control and freezing of gait, it is not yet fully clear why certain patients with PD fall more often than others (Ashburn *et al*., 2001b; Bloem *et al*., 2004). Gait variability during usual walking has been independently associated with fall risk in community living older adults, in patients with Alzheimer's disease, and in patients with PD (Nakamura *et al*., 1996; Hausdorff *et al*., 1997, 2001; Maki, 1997; Schaafsma *et al*., 2003). The sensitivity of gait variability to a secondary task in PD, but not in the healthy controls (who did not have a history of falling) may explain why gait variability is associated with fall risk in PD; dual tasking simulates more challenging situations of daily life (Bloem *et al*., 2001; Verghese *et al*., 2002a) and widens the gap between a healthy and pathological response (recall Fig. 2). More than that, Bloem *et al*. (2001) suggested that while healthy controls give priority to a postural task (even at the cost of mistakes in the secondary cognitive task), PD patients do not use this 'posture first' strategy, and this might increase their risk of falling (Bloem *et al*., 2001). Our study is consistent with this finding. In the most attention demanding task (serial 7 subtractions), control

subjects made mistakes on the cognitive task but kept their gait steadiness stable, while PD patients could not maintain their gait steadiness (maybe because they required more attention for the cognitive task). This dependence also suggests that assessment of gait variability under dual tasking conditions may further improve fall prediction.

Nature of secondary tasks and competing models of dual tasking

A number of models have been proposed to explain observed dual tasking decrements (Pashler, 1994; Sharon, 1997; Schmidt & Timothy, 1999; Ruthruff *et al*., 2001; O'Shea *et al*., 2002). Dault *et al*. (2003) suggested that articulation is the reason that serial 7 subtractions affects postural control in healthy adults and that this task should be viewed as a complex motor task. This explanation is consistent with the bottleneck theory that proposes that when two tasks are similar in their nature (e.g. two motor tasks) and utilize common neural resources, a bottleneck will be created in the information processing that reduces performance (Pashler, 1994; Sharon, 1997; Schmidt & Timothy, 1999; Ruthruff *et al*., 2001; O'Shea *et al*., 2002). Conversely, O'Shea *et al*. (2002) suggested that their comparison of the effects of serial subtractions and a motor task on gait support the capacity sharing model. According to this model, performance of two attention demanding tasks reduces the functioning of one or both tasks, if capacity limits are exceeded, regardless of the specific nature of the tasks. One could argue, however, that serial subtractions is a motor task and therefore that the bottleneck model cannot be excluded. In contrast, the present findings clearly favour the capacity sharing model over the bottleneck model. As seen in Table 2, dual tasking altered gait (e.g. speed and swing time), in both groups, even when the secondary task had no motor component. As serial 7 subtractions has both cognitive and motor elements, one cannot completely rule out the cross talk theory (Pashler, 1994; Sharon, 1997; Schmidt & Timothy, 1999; O'Shea *et al*., 2002). Nonetheless, the present results are most consistent with the capacity sharing model, or at least with a modified version that proposes that as attention is split, dividing attention, performance of two attention demanding tasks may be altered, even if capacity is not yet exceeded.

Switching perspectives and considering gait as the 'secondary task' provides further insight into the gait deficits in PD. While walking (a motor task) did not have a marked effect on listening comprehension (a cognitive task), in either PD or controls, the combination of walking and phoneme monitoring decreased performance on this cognitive task, in both groups (Table 3). This behaviour is consistent with the capacity sharing model. In addition, it underscores the idea that the dual task decrement in gait rhythmicity is not simply a reflection of a general decline in dual tasking abilities in PD, but rather it reflects PD-specific impairment in gait. The effects of dual tasking on the cognitive listening task and on gait speed are similar in PD and controls; still, dual tasking markedly increases stride time variability and swing time variability in the patients with PD, but not in the controls.

One could speculate that fatigue may have influenced the results in the patients with PD, however, examination of the order of testing suggests that this was not likely the case. The order of the gait tests was simple task, complex task, usual walking, and then serial 7s. If fatigue had a major effect on the results, we would have expected fatigue to affect the usual walking condition (performed third) as well as the serial 7 condition (performed fourth). However, the usual walking measures of gait were 'better' than those of all other conditions (e.g. highest gait speed and lowest variability, in both groups), consistent with the idea that the best gait occurs when no dual tasks are added. Thus, it seems likely that any fatigue effects played a minor role.

Cognitive function and gait

Patients with PD generally did significantly worse on the tests of executive function compared to the control subjects (recall Table 4). In contrast, on tests of memory (recognition tests), no significant differences were found. Similarly, PD patients performed as well as controls on the tests of listening comprehension and phoneme monitoring (recall Table 3). These results are consistent with previous reports (Lees & Smith, 1983; Dubois & Pillon, 1997; Uekermann *et al*., 2004) which describe impairment in executive function and attention abilities as the most prominent cognitive changes in PD patients, even in the early stages of the disease.

There was a small, but significant association between executive function measures and gait variability during usual walking conditions. This association tended to increase during the complex walking task and increased further during the serial 7s task (from a *posthoc* vantage point, clearly the most difficult task). This was true for both stride time variability and swing time variability. Similar findings were recently reported in patients with Alzheimer's disease (Sheridan *et al*., 2003). In that study, gait variability and executive function were not related in the usual walking condition, but a significant association was found when gait was accompanied by a cognitive task. In a study of nondemented older adults, Ble *et al*. (2005) also observed that the association between executive function and lower extremity function increased when the gait task became more complex (i.e. during obstacle course walking). The present results suggest, therefore, the possibility that the cognitive decline seen in patients with PD might exacerbate the difficulties these patients already have in maintaining gait steadiness and rhythmicity and this might lead to an increased risk of falling, in particular when patients are required to attend to gait and another task. This is consistent with the view that impaired internal cueing mechanisms in PD transforms gait rhythmicity into an attention-demanding.

Clinical implications and limitations

The present findings suggest the possibility that measures of gait variability during dual tasking may provide a sensitive marker of fall risk and that enhancement of cognitive function may reduce fall risk. Our study also raises three other important clinical issues about the role of dual tasking. (i) Is it possible to train patients to improve their cognitive abilities in order to handle better a variety of dual tasking situations that are common in daily life, thereby decreasing fall risk? (ii) Alternatively, would an intervention program that teaches patients with PD to avoid dual tasking during walking reduce their fall risk? (iii) Finally, given the association between executive function and dual tasking performance, it is interesting to speculate about the possibility of treating gait disturbances by intervening in the cognitive domain in general, and through attention-enhancing medications or therapies more specifically. Cholinesterase inhibitors have been shown to improve executive function and attention in PD patients with dementia (Giladi *et al*., 2003; Emre *et al*., 2004), but the effects on nondemented patients with PD and on gait and fall risk remain to be determined. While large scale, prospective studies are needed to evaluate these questions, our findings suggest that interventions and therapies designed to ameliorate gait disturbances in PD should also emphasize cognitive aspects.

This study has a number of limitations. The patients in the PD group were relatively homogeneous; all were stages 2–3 on the Hoehn and

Yahr scale and did not have motor response fluctuations. Non-fluctuating patients with relatively moderate disease progression were chosen to minimize the confounding effects of medication wear-off. In patients with motor response fluctuations, one has to carefully control for peaks and troughs in performance due to the medication effect. Given the duration of the study, we tried to alleviate this problem by studying patients who did not have motor response fluctuations. Another reason for choosing such patients is that patients in Hoehn and Yahr stages 4–5 might have great difficulties with walking (especially in stage 5) and dual tasking could potentially be unsafe. However, that the study of this patient group limits, to some degree, the ability to generalize the findings. Nonetheless, we assume – of course, this needs to be confirmed, that as the disease progresses, observed differences between the control and patient groups will grow. As both motor and cognitive function tend to decline with disease progression in PD, one can speculate that the effects of dual tasking will also become more profound as the disease progresses. To generalize the present findings, it would be interesting to evaluate the effects of dual tasking and the relationship to cognitive function in PD patients who are not yet taking antiparkinsonian medications as well as in patients with more advanced disease. In those patients, study of the effects of levodopa on dual tasking abilities would also provide further insight into mechanisms. In addition, in order to more fully understand the role of cognitive impairment, it would be helpful to further refine the study of the relationship between dual tasking, gait, and subtypes of executive and frontal dysfunction, including tests of working memory, in a larger, more heterogeneous cohort.

The present findings demonstrated that dual tasking has disparate effects on gait speed and gait variability. One can speculate about the factors that contribute to this disparity, but a complete explanation is still lacking. Regardless of the precise mechanisms, the present findings indicate that certain aspects of gait are attention-demanding, in both healthy, older adults and patients with PD (e.g. gait speed), while the regulation of gait rhythmicity and stride-to-stride variability normally does not tax attention.

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Abbreviations

MMSE, Mini-Mental State Exam; PD, Parkinson's disease; UPDRS, Unified Parkinson's Disease Rating Scale.

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