

## Dual-task Interference Disrupts Parkinson's Gait Across Multiple Cognitive Domains

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**Abstract**—Gait dysfunction, a hallmark of Parkinson's disease, contributes to a relatively high incidence of falling. Gait function is further diminished during the performance of a motor-cognitive task (i.e., dual-task). It is unclear if Parkinson's disease-related dual-task deficits are related to a specific area of cognitive function or are the result of a more global decline in executive function. The aim of this project was to systematically evaluate gait performance to determine if gait dysfunction is restricted to certain types of executive function or a global phenomenon in individuals with Parkinson's disease. Twenty-three individuals with mild-moderate Parkinson's disease completed a series of dual-task conditions in which gait was paired with cognitive tasks requiring: working memory (0, 1, and 2-back), attention and problem solving (serial-7 subtraction), verbal memory (digit recall), semantic memory (Controlled Oral Word Association) and information processing speed (visual Stroop test). The results demonstrate that individuals with mild-moderate Parkinson's disease have a generalized worsening of spatial-temporal gait parameters regardless of the specific cognitive demand being performed concurrently. Overall, gait velocity decreased ( $p < 0.01$ ) and stride and stance time both increased ( $p < 0.01$ ) across all cognitive conditions. The attention and problem solving task resulted in the greatest number of gait parameter decrements. Results indicated that performance on cognitive tasks remained unchanged from single-task to dual-task conditions. Diminished gait performance under dual-task conditions across different cognitive function domains suggests a global Parkinson's disease-related deficit in information processing and regulation of gait. © 2018 IBRO. Published by Elsevier Ltd. All rights reserved.

**Key words:** gait, cognition, dual-task, Parkinson's disease.

### INTRODUCTION

Parkinson's disease (PD) is a neurological disorder associated with the selective loss of dopaminergic neurons within the basal ganglia, resulting in motor and non-motor symptoms (Bartels and Leenders, 2009). Gait and cognitive dysfunction are two disabling features of PD (Cooney and Stacy, 2016; Moustafa et al., 2016) that contribute to an increased risk of falling (Gray and Hildebrand, 2000; Wielinski et al., 2005). Falling in the PD population have both social (Hajek and Konig, 2017) and health-related implications as over 50% of individuals with PD report falls, and of

those that fall, 65% require follow-up medical intervention (Wielinski et al., 2005).

Changes in gait and cognitive function associated with PD have historically been evaluated and treated independent of one another; however data clearly indicate cognition and gait performance are linked (Horak, 2006; Yogev-Seligmann et al., 2008, 2013; Rochester et al., 2014). Dual-task constructs provide an environment that allows for manipulation of motor-cognitive tasks to evaluate the gait-cognition relationship. Previous studies indicate that the addition of an attention-demanding, problem solving, memory or visual-spatial processing task while walking results in gait deterioration, cognitive function, or both in PD (Yogev et al., 2007; Kelly et al., 2012; Yogev-Seligmann et al., 2013; Rochester et al., 2014; Stegemoller et al., 2014); however studies only evaluated one aspect of cognitive function (e.g. attention-demanding task) in the dual-task testing environment, therefore, limiting the applications of the outcomes to

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**Abbreviations:** 2MWT, 2-min walk test; ANOVA, analysis of variance; CAREN, Computer Assisted Rehabilitation ENvironment; COWA, Controlled Oral Word Association; LA, less affected; MA, more affected; MDS-UPDRS, Movement Disorders Society Unified Parkinson's disease rating scale; PD, Parkinson's disease.

only a single and specific aspect of cognitive function (e.g. attention, memory, etc.).

The gait-related declines noted under dual-task paradigms in PD are disproportionately greater than that exhibited in age-matched healthy controls (Yogev-Seligmann et al., 2013). It is proposed that PD-related basal ganglia dysfunction is responsible for greater difficulty performing dual-tasks as the nigrostriatal dopaminergic pathway is involved in the processing and modulating of both cognitive and motor functions (Bartels and Leenders, 2009; Peterson and Horak, 2016). In PD, neural pathways are disrupted as the degeneration of dopaminergic projections places individuals at a deficit in resources available for the simultaneous processing of information and gait monitoring under dual-task conditions. The basal ganglia-thalamo-cortical circuits are involved in coordinating and connecting tasks. The coordination of activities, such as a motor-cognitive task, are dependent on parallel circuits that pass through the basal ganglia which aids in processing input from multiple brain regions to help to regulate output. In PD, gait function abnormalities arise from the degeneration of the basal ganglia, as both motor and cognitive processes compete for the limited resources available for processing information and coordinating task (DeLong and Wichmann, 2007; Lewis and Barker, 2009; Galvan et al., 2015; Peterson and Horak, 2016).

Clinical measures demonstrate a unilateral to bilateral progression of PD symptoms, including gait dysfunction, across the continuum of the disease. Systematically evaluating both the more affected (MA) as well as the so-called less affected (LA) side has the potential to provide greater insights into disease progression, in particular as it relates to changes in gait. Asymmetrical gait features are more apparent in fallers compared to non-fallers, especially during the swing phase of gait (Lord et al., 2016). The precise characterization of bilateral function, even in those considered “unilaterally affected” may lead to more precise and early interventions aimed at reducing lower extremity impairment. However, there are a limited number of investigations aimed at characterizing differences between MA and LA sides during gait, especially under dual-task conditions that span multiple types of executive functioning tasks (Yogev et al., 2007; Rochester et al., 2014).

Our previous work has characterized postural stability changes under dual-task conditions (Alberts et al., 2008; Frankemolle et al., 2010), while others have described gait changes that occur under dual-task conditions. A gap exists related to how basal ganglia dysfunction associated with PD impacts bilateral gait patterns under dual-task conditions that require different types of cognitive function. Associations between different aspects of cognition and gait performance under dual-task conditions in PD have been identified (Kelly et al., 2012; Stegemoller et al., 2014), but specific gait deficits and type of cognitive task utilized during evaluations vary widely across studies and have not produced consistent results (Kelly et al., 2012; Rochester et al., 2014; Stegemoller et al., 2014; Salazar et al., 2017). It is unknown whether or not a specific aspect of cognition or executive function requires

a greater amount of cognitive resources than others, which would result in either greater cognitive deficits, gait deficits, or both cognitive and gait deficits under dual-task conditions. The use of a wide range of cognitive tasks that target different aspects of cognition while simultaneously measuring gait in PD could provide valuable insight into which aspect of cognition results in the greatest gait deficits under dual-task conditions. The approach of utilizing a wide range of cognitive tasks that stress different aspects of cognition under dual-task conditions in PD has not been systematically evaluated. Five major areas of cognitive function were evaluated under dual-task conditions in which a cognitive task was performed in concert with a gait task: working memory (N-back) (Leon-Dominguez et al., 2015), attention and concentration (serial-7 subtraction) (Karzmark, 2000), attention and working memory (digit recall) (Richardson, 2007), semantic and verbal fluency (Controlled Oral Word Association) (Pettit et al., 2013; Shao et al., 2014), and information processing speed (Stroop test) (Brown and Marsden, 1988; Stroop, 1992). The primary aim of this project was to systematically manipulate cognitive function under dual-task conditions to precisely characterize biomechanical changes in gait in individuals with mild to moderate PD. Due to the potential of gait asymmetry to contribute to falls, a secondary aim was to evaluate gait asymmetry under dual-task conditions in individuals with mild-moderate PD. We hypothesize that all aspects of cognition will contribute to gait decrements due to the parallel neural circuits that compete for resources passing through the basal ganglia.

## EXPERIMENTAL PROCEDURES

### Participants

A total of 24 individuals were enrolled, one participant was excluded from analysis due to inability to complete the cognitive tasks. All analyses were completed using data from the remaining 23 participants. Participant demographic information is provided in Table 1.

Individuals with idiopathic PD, Hoehn & Yahr 2–4, who were able to ambulate 300 feet without assistance were eligible for the study. Exclusion criteria included any medical or musculoskeletal contraindication to ambulation or exercise (Thompson et al., 2013), a history of a stroke, a diagnosis of dementia, inability to follow two-step commands, having had any PD-specific surgical intervention (i.e., deep-brain stimulation), or three or more errors on the Short Portable Mental Status Questionnaire (Pfeiffer, 1975). Participants were initially screened via phone to ensure eligibility. All participants reviewed and signed an informed consent form that was approved by the Cleveland Clinic Institutional Review Board prior to participation.

### Clinical and cognitive assessments

All data were collected during a single visit, while ‘on’ antiparkinsonian medication, 1-h post antiparkinsonian medication administration. The Movement Disorders Society-Unified Parkinson’s disease Rating Scale

**Table 1.** Participant demographics

Participant	Age (yrs.)	Sex	Disease duration (yrs.)	UPDRS motor III score	Falls in past 12 months	SPMSQ errors
1	71	M	5.5	35	0	0
2	56	F	8	31	0	0
3	69	F	1.5	44	1	0
4	70	F	5	22	0	0
5	58	M	8	46	3	2
6	56	F	0.5	27	0	1
7	64	F	15.5	25	0	1
8	67	M	5.5	28	0	0
9	54	M	5.5	18	1	0
10	68	M	4	16	0	0
11	73	M	5	47	0	0
12	72	F	5	41	2	0
13	60	F	10.5	19	1	0
14	69	M	3	44	1	0
15	61	M	9	32	0	0
16	56	F	4	64	20	0
17	63	F	11	29	1	1
18	76	F	6.5	22	1	1
19	56	F	7	18	3	0
20	59	M	2	28	40	0
21	66	F	1.5	27	8	0
22	51	M	4.5	35	3	0
23	69	M	15.5	60	4	2
Mean	63.7	11M	6.2	33.0	3.9	0.35
SD	7.0		4.0	13.1	9.0	0.65

Short Portable Mental Status Questionnaire (SPMSQ) Errors are the number of incorrect responses given on the SPMSQ.

(Goetz et al., 2008) Motor III (MDS-UPDRS) exam was performed by a single rater for all participants. Cognitive function was evaluated under single-task conditions while seated. The following cognitive tasks were presented in a randomized order across participants: N-back (0-back, 1-back and 2-back conditions), serial-7 subtraction, digit recall, Controlled Oral Word Association (COWA) and visual Stroop test. Serial-7 subtraction had a duration of two minutes for comparison to the standardized 2-minute walk test (2MWT). Serial-7 subtraction began with a random 3-digit number between 300 and 500 and the total number of correct answers was recorded. Digit recall's duration was variable depending on the correct responses from the participant, and the longest string of numbers correctly repeated was recorded. COWA task was a 60-s trial (Lezak, 1995) in which the participant was asked to name as many words as possible that began with a specific letter of the alphabet, and the total number of non-repeating words were recorded. The N-back and Stroop tests used a projection screen with letters or words displayed every two seconds (Smulders et al., 2012) during a 60-s trial to match the duration of the verbal fluency test and the total number of correct responses was recorded.

### Gait assessment

Following the clinical and cognitive assessment, each participant performed a gait assessment under single and dual-task conditions. The cognitive tasks described above were repeated under dual-task conditions with biomechanical data captured using the Computer

Assisted Rehabilitation ENvironment (CAREN) (Motekforce Link, Amsterdam, Netherlands) system (van der Eerden et al., 1999) and is shown in Fig. 1. The CAREN system consists of a 10-camera 3D motion capture system (Vicon Inc., Oxford, UK), D-Flow control software (Motekforce Link), 180° curved projection screen and a six degree of freedom motion platform (Moog Inc., Elma, New York) with a treadmill (Bertec Corp., Columbus, Ohio). Under single-task and dual-task conditions, the same background was displayed on the projection screen (a straight gray path). Under both single-task and dual-task conditions we asked the participants to focus their gaze on the screen. A total of 31 retroreflective markers were placed on anatomic landmarks on the lower extremities to characterize gait function (van den Bogert et al., 2013).

To analyze single-task gait, a 2MWT was performed on the CAREN system under a self-paced paradigm on a treadmill. A self-paced treadmill speed algorithm, as described by Sloot et al. (2014), incorporates anterior-posterior pelvis position relative to the center of the treadmill, and was used for all gait conditions. The retroreflective marker position data were filtered using a 2nd-order low-pass Butterworth filter with a 6-Hz cut-off frequency. The Human Body Model (van den Bogert et al., 2013) was used to calculate spatial-temporal parameters of gait during self-paced ambulation under single and dual-task conditions. The order of the dual-tasks was block randomized across participants. Participants were not given instructions for the priority of one task over the other and rest breaks were given between each of the dual-task walks.



**Fig. 1.** Computerized Analysis Rehabilitation ENvironment (CAREN) extended virtual reality system during the 2-back test.

**Fig. 2** illustrates how gait cycles were determined; defined as heel strike to heel strike of the same foot. Each peak in the heel marker data represents a heel strike, while every valley in the toe data represents a toe off (Zeni et al., 2008). Heel strike was verified using the posterior heel marker positions. Spatial-temporal parameters cadence (steps/minute), gait velocity (center of mass velocity), stride time variability, step length variability, and step width variability, were calculated for each gait cycle and the average for each trial was used for analysis in each condition. The variability metrics were calculated using calculations from Galna et al. (2013). Since PD tends to have a MA side in mild to moderate cases, gait asymmetry was evaluated. To analyze asymmetry, gait cycles were separated into a MA and LA side for the following gait parameters for additional analysis: step length, step width, stride time, swing time, and stance time.

### Data analysis

Normality of the cognitive scores was tested using Shapiro–Wilk test of normality. Three of seven different cognitive tests failed to achieve normality. To assure uniformity in using testing procedure across all the cognitive tests, paired samples Wilcoxon tests were used to detect differences in cognitive scores between single and dual-task conditions on the 0-back, 1-back, 2-back, serial-7 subtraction, digit recall, COWA, and Stroop tests.

Repeated measures linear mixed effects models were used to model the effects of the different cognitive dual tasks (0, 1, and 2-back, serial-7 subtraction, digit recall,

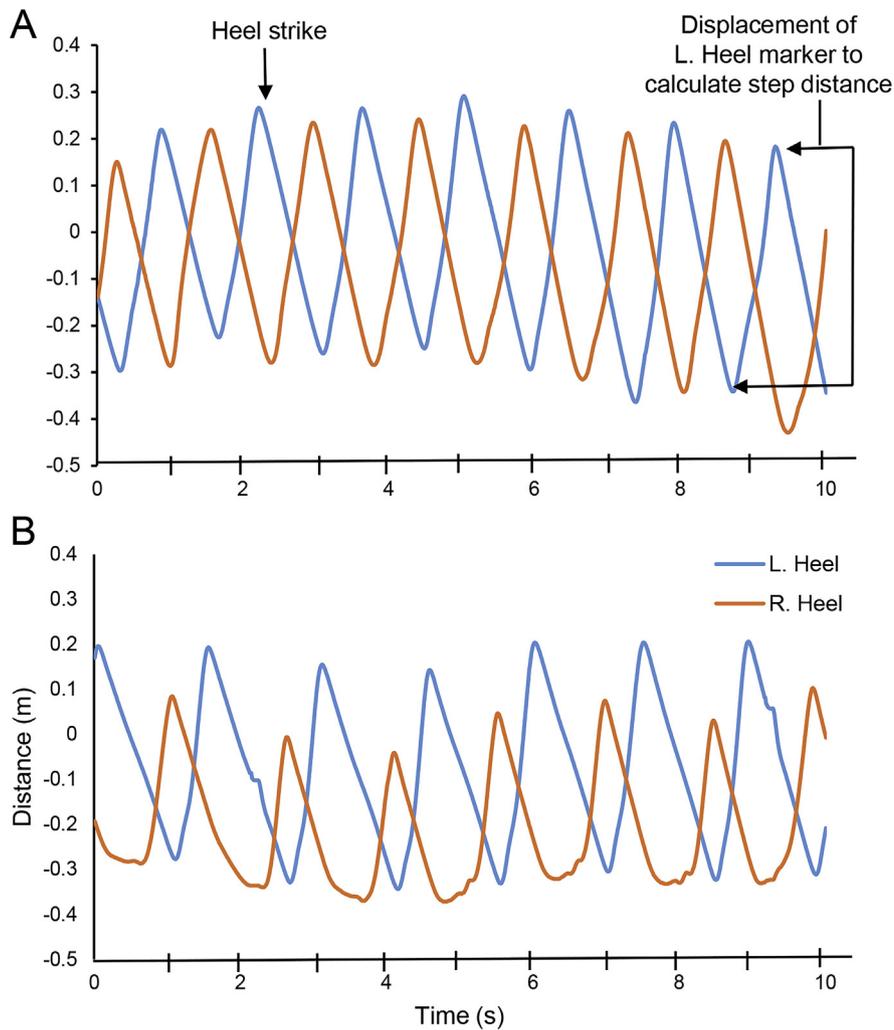
COWA, and Stroop tests) and single-task on gait performance as measured by the spatial-temporal parameters of cadence, velocity, and measures of variability, separately. An analysis of variance (ANOVA) technique was performed on each of three models, separately, to detect the overall effect of different tasks on the dependent variables. When the ANOVA model resulted in significant differences in comparison from single to dual-task, a post hoc pairwise comparison, and Tukey's tests, were performed to identify which tasks were significantly different from each other. The  $p$ -values in multiple comparisons were adjusted using the Bonferroni correction. The pairwise comparison was evaluated based on approximate Z test. Based on Bartlett's test the equality of the variances was achieved in context of the ANOVA models. Repeated measures linear mixed effects models were used to model the relationship between the independent variables sides, which has two factors: MA and LA and the tasks, which has seven factors as mentioned earlier to the dependent variables step length, step width, stride time, swing time and stance times separately. The performance of the relationship was assessed using a two-way ANOVA model. Like earlier, if the ANOVA resulted in overall significance of the model, Tukey's tests with Bonferroni corrections to the  $p$ -values were performed. In the above model the two factors of the sides were determined from self-report from participants and confirmed with UPDRS scores, during single and dual-task conditions. All statistical testing was performed at the 5% level of significance. Statistical analysis was completed using the R statistical program (version 3.3.2).

## RESULTS

### The effects of different aspects of cognition on gait cadence, velocity and variability

There were no significant differences in cognitive scores between single and dual-task conditions ( $p > 0.05$ ) for all cognitive tasks. Cognitive scores are provided in Table 2.

Although cognitive performance did not change between single and dual-task conditions, there was a dual-task effect across all cognitive tests for gait parameters (Table 3). Step cadence ( $F_{7, 154} = 5.38$ ,  $p < 0.001$ ,  $\eta^2 = 0.024$ ), gait velocity ( $F_{7, 154} = 4.77$ ,  $p < 0.001$ ,  $\eta^2 = 0.054$ ) and measures of step length variability ( $F_{7, 154} = 3.31$ ,  $p < 0.001$ ,  $\eta^2 = 0.040$ ) significantly worsened under dual-task conditions when compared to single-task gait, but there was no



**Fig. 2.** Representative raw heel marker data in the anterior-posterior direction over same time series is shown for both single and dual-task gait from the same participant. Peak amplitude of the heel markers represents heel strike and is shown above for right and left foot. (A) Example of single-task gait (B) Example of dual-task gait. Decreased cadence (steps/min) during dual-task gait is shown by the increase in distance between peaks over time, and decreased step length (m) during dual-task gait is shown as the distance the heel markers travels in the A-P direction is decreased for the right heel, which is the more affected PD side.

significant difference ( $p > 0.05$ ) in step cadence, gait velocity and variability between the different types of cognitive loading. Step cadence and gait velocity were both significantly slower ( $p \leq 0.01$ ) than single task gait

during all seven of the dual-tasking conditions. The attention and problem solving task (serial-7 subtraction) resulted in nearly a 20% decrease in gait velocity and 15% decrease in step length when compared to single task gait alone. The variability of step length significantly decreased ( $p \leq 0.05$ ) from single-task gait under the 2-back, serial-7 subtraction, verbal fluency and Stroop conditions, but not digit recall ( $p = 0.056$ ). There was no significant change ( $p > 0.05$ ) for stride time variability or step width variability under all dual-tasking conditions.

### The effects of different aspects of cognition on MA and LA side while walking

A two-way ANOVA, was utilized to evaluate the gait variables of step length, step width, stride time, swing time and stance time of the MA and LA sides during single and dual-task gait. Results indicated a main effect of side ( $p \leq 0.001$ ) for swing time only, but neither the test nor interaction between test and side were significant.

### The effects of different aspects of cognition on step length, width, stride and stance time

Since the two-way ANOVA did not reveal a statistical significance of the main effect of side ( $p > 0.05$ ) for step length, step width, stride time and stance time, the data were collapsed and a repeated measures ANOVA was used to analyze the data. The repeated measures

ANOVA, based on nonlinear mixed effects models, resulted in a significant main effect for cognitive task as participants took significantly shorter steps ( $F_{7, 154} =$

**Table 2.** Cognitive scores

Cognitive task	Single-task score	Dual-task score
0-Back (max score 30)	30 [30, 30]	30 [30, 30]
1-Back (max score 29)	29 [29, 29]	29 [29, 29]
2-Back (max score 28)	25 [22, 27]	26 [25, 27]
Serial-7 subtraction (# correct)	26 [13.5, 34.5]	26 [15.5, 34.5]
Digit recall (longest digit recalled)	6 [5.5, 7]	6 [5, 7]
COWA (number of words)	17 [13.5, 19.5]	17 [13.5, 18]
Stroop (max score 30)	30 [28.5, 30]	30 [28, 30]

Data presented as median [first quartile, third quartile]. Scores: Serial-7 subtraction-total number of correct answers in two minutes; Digit recall-the longest string of numbers correctly repeated; COWA- total number of non-repeating words in 60 s; The N-back and Stroop tests- total number of correct responses in 60-s.

**Table 3.** Gait variables for each cognitive task

Gait variable	Single-task gait	0-Back	1-Back	2-Back	Serial-7 subtraction	Digit recall	COWA	Stroop
Step cadence (steps/min)	118.42 (11.55)	113.82 (12.65) <sup>*</sup>	112.78 (14.23) <sup>*</sup>	113.83 (13.23) <sup>*</sup>	111.09 (15.40) <sup>*</sup>	112.59 (14.08) <sup>*</sup>	111.81 (13.26) <sup>*</sup>	113.17 (13.54) <sup>*</sup>
Velocity (m/s)	1.24 (.21)	1.09 (.27) <sup>*</sup>	1.08 (0.26) <sup>*</sup>	1.07 (.23) <sup>*</sup>	1.05 (.30) <sup>*</sup>	1.09 (.25) <sup>*</sup>	1.10 (.27) <sup>*</sup>	1.09 (.26) <sup>*</sup>
Step length (m)	.62 (.10)	0.56 (0.13) <sup>*</sup>	0.56 (0.13) <sup>*</sup>	.55 (.12) <sup>*</sup>	.53 (.14) <sup>*</sup>	.57 (.12) <sup>*</sup>	.57 (.12) <sup>*</sup>	.56 (.11) <sup>*</sup>
Step width (m)	.11 (.04)	0.12 (.04) <sup>*</sup>	0.12 (.05) <sup>*</sup>	.12 (.05) <sup>*</sup>	.12 (.05) <sup>*</sup>	.12 (.04) <sup>*</sup>	.12 (.05) <sup>*</sup>	.12 (.05) <sup>*</sup>
Stride time (sec)	.99 (.11)	1.02 (.12) <sup>*</sup>	1.03 (.13) <sup>*</sup>	1.03 (.13) <sup>*</sup>	1.06 (.17) <sup>*</sup>	1.04 (.14) <sup>*</sup>	1.04 (.14) <sup>*</sup>	1.04 (.15) <sup>*</sup>
<i>Swing time (sec)<sup>‡</sup></i>								
MA	.32 (.04)	0.32 (.04)	0.32 (.05)	.33 (.04)	.33 (.05)	.33 (.04)	.33 (.05)	.33 (.05)
LA	.32 (.03)	0.32 (.04)	0.32 (.04)	.32 (.03)	.32 (.04)	.32 (.04)	.33 (.03)	.32 (.03)
Stance time (sec)	.66 (.08)	0.70 (.09)	0.70 (.09)	.70 (.10) <sup>*</sup>	.72 (.13) <sup>*</sup>	.71 (.12) <sup>*</sup>	.71 (.11) <sup>*</sup>	.70 (.12) <sup>*</sup>
Step length variability	.15 (.02)	0.13 (.02) <sup>*</sup>	0.14 (.02) <sup>*</sup>	.13 (.02) <sup>*</sup>	.14 (.02) <sup>*</sup>	.14 (.02) <sup>*</sup>	.14 (.02) <sup>*</sup>	.13 (.02) <sup>*</sup>
Step width variability	.20 (.05)	0.22 (.07) <sup>*</sup>	0.21 (.06)	.21 (.05)	.22 (.06)	.21 (.05)	.20 (.05)	.20 (.06)
Stride time variability	.17 (.03)	0.19 (.05)	0.18 (.04)	.17 (.03)	.19 (.03)	.19 (.04)	.18 (.04)	.17 (.02)

Data presented as mean (standard deviation). MA = more affected Parkinson's side; LA = less affected Parkinson's side.

<sup>\*</sup> Indicates a significance ( $p < .05$ ) comparing single-task gait to dual-task gait.

<sup>‡</sup> Indicates significant difference between MA and LA sides.

3.69,  $p < 0.05$ ,  $\eta^2 = 0.036$ ) under dual-task conditions. In addition to taking shorter steps, participants also took wider steps, as step width significantly increased ( $F_{7, 154} = 3.92$ ,  $p < 0.001$ ,  $\eta^2 = 0.005$ ) from  $0.11 \pm 0.04$  m during single-task gait to  $0.12 \pm 0.05$  during all dual-task conditions. Stride time increased ( $F_{7, 154} = 5.71$ ,  $p < 0.001$ ,  $\eta^2 = 0.019$ ) under all dual-task conditions, and is a function of stance time increasing ( $F_{7, 154} = 5.22$ ,  $p < 0.001$ ,  $\eta^2 = 0.024$ ) under all dual-tasking conditions. Post hoc analysis revealed a significant difference in step length ( $p < 0.05$ ) between serial-7, 0-back, 1-back and 2-back tasks. The greatest difference in step length was found during the serial-7 subtraction condition as step length decreased from  $0.62 \pm 0.10$  m during single-task gait to  $0.53 \pm 0.14$  m during the serial-7 condition. There was a significant difference in step width ( $p < 0.05$ ) between serial-7, 0-back, 1-back, 2-back, Stroop, and verbal fluency tasks. The significant difference in stride time ( $p < 0.05$ ) was identified between all tasks except 0-back task with stride time being the longest in duration under the serial-7 condition ( $1.06 \pm 0.17$  s). Stance time significantly ( $p < 0.05$ ) differed in all tasks except 0-back task. The longest duration of stance time was during the serial-7 condition ( $0.72 \pm 0.13$  s).

## DISCUSSION

The primary aim of this project was to determine the impact of specific aspects of cognition on gait dysfunction in individuals with PD. The gait declines in all spatial-temporal parameters, with the exception of step width variability and stride time variability, suggest that individuals with mild-moderate PD have a generalized worsening of spatiotemporal gait parameters, regardless of the degree of task difficulty, when an attention, memory, information processing, visuospatial or verbal memory task are being performed concurrently. The difficulty of the N-back test was

manipulated by altering the number of letters that had to be remembered in a list (0, 1 and 2 letters back). Gait decrements were observed during all levels of difficulty, while cognitive performance was preserved.

An important finding of the present study is that gait velocity changed from an average of 1.24 m/s during single-task gait to 1.10 m/s or less during all dual-task conditions. Serial-7 subtraction and 2-back resulted in the greatest decrease in gait velocity as they decreased to 1.05 and 1.07 m/s respectively. On average, gait velocity decreased by 0.17 m/s during dual-tasking conditions, which falls in the range of the minimal clinically important difference of 0.10–0.20 m/s for gait speed in adults with pathology (Bohannon and Glenney, 2014). Walking at slower gait speeds has been shown to be the strongest predictor to falling in individuals with mild PD (Lord et al., 2016). Specifically, PD patients with gait velocity of 1.13 m/s or slower are eight times more likely to fall (Lord et al., 2016). The substantial decrease in gait velocity when moving from single to dual-task conditions while preserving cognitive performance indicates that in individuals with PD, the basal ganglia is unable to sufficiently process both motor and cognitive demands under dual-task conditions to an extent that places individuals at an increased risk of falling.

A secondary aim of the present study was to evaluate gait asymmetry under dual-task conditions. Interestingly, gait decrements under dual-task conditions were observed uniformly bilaterally and during all cognitive tasks, with the exception of swing time as analysis revealed a difference between MA and LA sides. Previous studies that observed gait asymmetries were completed overground with gait measurements taken using instrumented floor mats (Galna et al., 2013; Rochester et al., 2014), or force sensitive insoles placed in participant shoes (Plotnik et al., 2005; Baltadjieva et al., 2006). Galna et al., observed gait impairment progression in those with PD and healthy older adults over a course of 18 months, and found individuals with PD

present with a significantly greater asymmetry in step time, swing time and stance time when compared to their healthy peers. Plotnik et al., and Baltadjieva et al., also found PD gait asymmetry during single-task gait in swing time alone (Plotnik et al., 2005; Baltadjieva et al., 2006). Rochester et al., that found step length asymmetry during an attention and verbal memory task (Rochester et al., 2014) while Yogev et al., reported an increase in swing time asymmetry during an attention and problem solving task (Yogev et al., 2007). The conflicting results from previous studies and the present study could be due to differences in walking surface (treadmill compared to overground). To our knowledge, this is the first study to observe gait swing time asymmetry across a range of tasks that targeted different aspects of cognition under dual-task conditions in those with PD.

The increase in stance time observed under dual-task conditions in the present study may also be linked to fall risk. Older adults with a fall history were found to have increased stance time during gait when compared to both older adults and younger adults who did not have a fall history (Hausdorff et al., 1997). In PD, the increase in stance time may be a compensatory mechanism to increase stability as it increases the amount of time spent with feet on the ground, especially when coupled with the slower gait velocity and asymmetrical swing phase of gait that we observed.

During dual-task gait, where gait dysfunction occurred regardless of the aspect of cognition function that was taxed, cognitive performance remained unchanged as there was no difference found between single and dual-task cognitive scores. Since cognitive performance remained intact under dual-task conditions, this suggests that individuals with PD prioritized the cognitive task over maintenance of gait performance, which supports the 'posture second' strategy (Bloem et al., 2006).

In PD, degeneration within the basal ganglia affects both motor and cognitive tracts (Bartels and Leenders, 2009; Galvan et al., 2015). The Limited Resource Hypothesis helps to explain the dual-task deficits observed in this project. The Limited Resource Hypothesis suggests that since cognition and motor function have parallel and overlapping neural networks within the central nervous system, there is a competition for the same limited resources (Wickens, 1980). When one task requires greater demand or resources, performance on one or both tasks is diminished. A recent brain imaging study comparing neural activation in both PD patients and healthy older adults during a motor-cognitive task supports the assumption that in PD parallel motor and cognitive neural circuits dysfunctionally overlap during a motor-cognitive task leading to greater cognitive-motor dysfunction (Nieuwhof et al., 2017). Since gait deteriorated under all dual-task conditions, it can be concluded that all aspects of cognition play a role in gait performance, with attention and problem solving task (serial-7 subtraction) perhaps requiring more cognitive resources as there was nearly a 20% decrease in gait velocity and 15% decrease in step length which was the greatest gait decrement noted during dual-task conditions.

The confirmation that dual-task conditions result in gait deficits regardless of the type of cognitive task being performed supports the need for further research that studies the effects of dual-task training, or gait and cognitive interventions, on individuals with PD. Future research that targets improving gait under dual-task conditions could be used to develop exercise recommendations or therapy for individuals with PD who aim to improve dual-task capabilities.

## CONFLICT OF INTEREST STATEMENT

The authors have no financial disclosures to report.

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