The Role of Attention in Walking in Parkinson's Disease

by

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Dedication Page

This thesis is dedicated to my parents, Janis and Ken, who have tirelessly supported my academic career for as long as I can remember. I would not have made it this far without all the philosophical discussions, fast left turns, and stories of planting trees.

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Abstract

Parkinson's disease affects both cognitive and motor function. The purpose of this study was to look at the role of attention and walking in people with Parkinson's disease (n = 15) as compared to a healthy, matched control group (n = 15). Participants completed a variety of cognitive tests designed to measure vigilance, executive control, and working memory. They then performed n-back tasks with fixed- and self-paced presentation of stimuli, while seated and while walking along a GAITRite® mat, in counterbalanced order. Walking variables included velocity, stride length, cycle time, and double support. Single-task results showed people with Parkinson's performed worse on tasks of executive control, walking velocity, and cycle time. Significant dual-task costs were found for most gait variables and n-back accuracy, with no difference between groups. Executive control predicted velocity in both groups, but not dual-task costs. These findings highlight the role of cognition in walking in Parkinson's.

List of Abbreviations and Symbols Used

AIC	Akaike's Information Criterion
CMI	Cognitive-Motor Interference
COV	Coefficient of Variation
DalCAB	Dalhousie Computerized Attention Battery
DT	Dual Task (a subtest of the DalCAB)
DTAQ	Dual-Task Activity Questionnaire
DTE	Dual-Task Effect(s)
Flanker Int.	Flanker Interference (a score on the DalCAB)
% GC	Percentage of Gait Cycle
GNG	Go/No-Go (a subtest of the DalCAB)
MDS-UPDRS	Movement Disorder Society Revision of the Unified Parkinson's Disease Rating Scale
ML	Maximum Likelihood
MoCA	Montreal Cognitive Assessment
PD	Parkinson's Disease
R^2_c	R^2 conditional
R^2_m	R^2 marginal
REML	Restricted Maximum Likelihood
RT	Reaction Time / Response Time
SRI	Stimulus-Response Interval
SRT	Simple Response Time
TMT	Trail-Making Test
TR	Target Rate

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Chapter 1: Introduction

For most people, walking does not seem to be a task that requires much attention. Malone and Bastian (2010, p. 1954) assert that "explicitly thinking about walking is normally the exception rather than the rule"—such exceptions, they elaborate, may occur due to demands associated with navigating hazardous or unusual environments, or as a result of coping with an injury. While walking may not normally feature as a subject of conscious attentional control, evidence from studies of dual-task walking and cognitive-motor interference (i.e., studies which pair walking with a concurrent cognitive task and examine the effect on both walking and performance on the cognitive task) suggest that attention and cognition do in fact play a role in everyday locomotion. In this thesis, I contribute to what is known about attention and the effects of dual tasks on walking in people with Parkinson's disease and a healthy, matched control group.

1.1 Parkinson's Disease

Parkinson's disease (PD) is a neurodegenerative disease that has received clinical attention since its first description in 1817 (Rodríguez-Violante, Cervantes-Arriaga, Fahn, & Tolosa, 2017). Approximately one percent of individuals aged 60 and older have PD, which is associated with neuron loss, neurotransmitter dysfunction, and the presence of Lewy bodies in the substantia nigra, limbic structures, and brain stem (Kehagia, Barker, & Robbins, 2010; Rodríguez-Violante et al., 2017; Svenningsson, Westman, Ballard, & Aarsland, 2012; Tysnes & Storstein, 2017). While symptoms can vary greatly between affected individuals—enough to call into question whether PD should be classified as a single disease or rather a collection of related diseases (Rodríguez-Violante et al.,

2017)—the defining clinical symptoms as recently published by the Movement Disorder Society include bradykinesia (i.e., movements are slowed and continue to diminish in speed throughout execution), rigidity, a resting tremor, and both a response to dopamine medication as well as dyskinesia side effects resulting from the medication (Postuma et al., 2015). Diagnosed PD is generally considered idiopathic, though a reasonable consensus attributes 5–10% of cases to genetic factors (Tysnes & Storstein, 2017).

The motor complications of PD can be functionally disruptive. One review of several studies reporting falls suggested that between 40–90% of people with PD are fallers (often defined as having a recent fall, although the definition of "recent" may vary between studies); furthermore, around 85% of people with PD experience gait disturbances within three years of diagnosis (Kelly, Eusterbrock, & Shumway-Cook, 2012). These motor problems are not the only symptoms, however—PD is also associated with cognitive problems across the domains of attention, executive control, and memory (Aarsland et al., 2017; Kehagia et al., 2010). People with PD have deficits across all three Posner and Petersen attention networks (Petersen & Posner, 2012; Posner & Petersen, 1990): alerting (achieving and maintaining a state of vigilance or alertness), orienting (selecting an object of focus and orienting one's attention to it), and executive control (higher-level, goal-oriented, top-down control of the attention system). Lou (2009), for example, administered the Attention Network Test (Fan, McCandliss, Sommer, Raz, & Posner, 2002) to individuals with PD and controls, and found the PD group had significantly slower reaction times, more errors, and different scores across the three attention networks of alerting, orienting, and executive control. Lou also found

greater mental fatiguability as defined by declines in performance across the entire ANT testing session.

Mild cognitive impairment—often assessed using the Montreal Cognitive Assessment (MoCA; Nasreddine et al., 2005)—and dementia are also hallmarks of PD. According to a recent review of PD's impact on cognition, mild cognitive impairment is found in 25–30% of those without dementia and is itself a predictor for a later dementia diagnosis (Aarsland et al., 2017). Dementia prevalence ranges considerably depending on the study, but can approach 50% of individuals within a 10-year period following diagnosis (Aarsland et al., 2017). One study that conducted a 20-year follow-up suggested that progression to dementia is "inevitable", with 83% prevalence in those who lived for all 20 years of assessments (Hely, Reid, Adena, Halliday, & Morris, 2008).

Aspects of these motor and cognitive symptoms are in the top ten priorities for research focused on Parkinson's disease, as identified by the James Lind Alliance's patient engagement initiative to establish priorities for research efforts. People with PD, clinicians and caregivers, and families and friends of individuals with PD contributed to the rankings, which when finalized saw the top six factors include balance problems and falls (#1), dementia (#5), and mild cognitive problems such as disturbances to memory, vigilance, decision-making, and processing speed (#6; Deane et al., 2014).

1.2 Cognition and Walking

Cognition is recognized as a factor that contributes to walking, particularly in populations for whom walking is effortful (Hausdorff, Yogev, Springer, Simon, & Giladi, 2005). Cognition is also related to walking in that people often engage in cognitive

processes while walking, whether through deliberate control of balance, planning a route through a crowd, or recalling and mentally updating a grocery list while searching for items on a shelf. As Al-Yahya et al. (2011) note, "purposeful locomotion" demands that one adapt as necessary to achieve their goals (requiring cognitive processes such as updating, orienting, selecting, and planning) in the face of environmental obstacles (e.g., uneven ground, objects or people in the way, signs and other visual distractions, etc.). As such, walking is not merely a repetitive task—it is a dynamic task that requires executive function to cope with often-changing sensory information by correcting and adjusting gait accordingly (Sheridan & Hausdorff, 2007).

One way to measure the contribution of cognition to walking is through dual-task walking. In this paradigm, an individual walks while simultaneously performing a concurrent, secondary task such as talking or mental arithmetic. The underlying logic is that if walking were a purely automatic, motor task, then there should be no interference. Thus, any observed interference suggests some relation between the walking and cognitive functions at play. Changes to walking or the performance of the concurrent task can be quantified using the following equation, which expresses the dual-task effect as a percentage change (Kelly, Janke, & Shumway-Cook, 2010):

$$\frac{dual\ task - single\ task}{single\ task} * 100\%$$

Although cognitive-motor interference (CMI) is an appropriate term to describe detriments to performance on either the cognitive or motor task, research has often focused specifically on motor deficits during dual-task walking, rather than cognitive effects (Kelly et al., 2012). For example, people with PD typically show motor "dual-task

costs", such as reduced speed and greater variability between strides (Al-Yahya et al., 2011; Kelly et al., 2012). Dual-task costs have potential value to clinicians in that they could be used to aid in diagnoses or the identification of abnormal gait; however, research is ongoing. It should also be noted that dual tasks could, in theory, either facilitate performance on both walking and the concurrent task, or instead facilitate performance on one at a cost to the other (Plummer & Eskes, 2015).

1.3 Cognitive-Motor Interference

Although the underpinnings of cognitive-motor interference remain under debate, dual-task costs (i.e., CMI) have been theorized to result from a limited resource model, either because of a bottleneck or a capacity constraint (Leone et al., 2017; O'Shea, Morris, & Iansek, 2002). Increases in cognitive-motor interference due to conditions like PD could be understood as motor functions becoming increasingly less automatic with disease progression, in addition to the emerging deficits to cognitive ability (Kelly et al., 2015; Yogev et al., 2005). Neuroimaging studies examining cognitive-motor interference have not converged upon a single area associated with negotiating CMI (such as the prefrontal cortex, which is an obvious candidate due to its association with executive functions), supporting the notion that dual tasking involves the interaction of multiple networks or brain regions (Leone et al., 2017). However, Leone et al. (2017) admit that the differential activation patterns are challenging to compare amidst differences in the types and demands of the cognitive tasks used in dual-task studies.

1.4 Concurrent Cognitive Tasks

When designing a study using dual-task walking, an appropriate concurrent cognitive task (to be performed while walking) must be selected based on the research goals. Typical tasks include reciting a list—e.g., male names—or performing mental arithmetic (Kelly et al., 2012a). Choosing a cognitive task often requires making a compromise between level of experimental control, minimizing participants' ability to form and employ response strategies (if the research goal is to gain knowledge of the cognitive processes involved, variance between participants due to task-specific strategy use may obscure underlying differences in cognitive ability, depending on how cognitive-motor interference is being measured), and achieving ecological validity (which is important for clinical applications of dual-task walking research). Several studies have compared different concurrent cognitive tasks (e.g., Montero-Odasso, Muir, & Speechley, 2012; Wrightson, Ross, & Smeeton, 2016), finding that the affected gait variables as well as the magnitude of the effect may vary slightly depending on the study, the particular cognitive task, and the cognitive task's complexity. However, a recent meta-analysis comparing single- and dual-task walking speeds as well as the rate of change between single- and dual-task velocity found that arithmetic, language, memory, and motor dual tasks all had significant negative impacts on velocity (Raffegeau et al., 2019). Raffegeau et al.'s meta-analysis also found dual-task costs to velocity regardless of participants' baseline velocity. While overall a variety of cognitive tasks elicit cognitive-motor interference as measured by dual-task effects, there may be unexplored factors between tasks that could account for some of the dual-task effects.

One specific factor which may vary between concurrent cognitive tasks and which has not been explored in a controlled manner is pacing: tasks may be either self-paced or paced by the experimenter (i.e., fixed-paced). In self-pacing, the concurrent task advances at a rate selected by the participant. One example is the common concurrent task of serial subtraction, in which participants are given a (usually three-digit) number and asked to continuously subtract a given number from it, such as three or seven. Other types of tasks require participants to respond to a set of stimuli presented at a fixed rate; these may be deemed "experimenter-paced", because an interval between items in the set of stimuli must be chosen during the programming of the task. An example of this task would be the auditory *n*-back task, in which participants indicate whether each item in a list presented auditorily at a fixed rate (e.g., a list of letters) is the same as the item that appeared *n*-times ago. Although previous research has tackled other aspects of task administration, such as the effect of instructions, little has been done to directly compare self-paced and experimenter-paced tasks. While both types of tasks are found in the literature, they are seldom found within the same study. Wrightson et al. (2016) did use both serial subtraction and *n*-back in a single study; however, they tested healthy adults, and it is unclear how one could isolate any variance in scores attributable solely to pacing. A study employing two pacing modes within the same task (e.g., a fixed-paced and self-paced *n*-back) is warranted to adequately address this methodological question. If an effect of pacing is found, it may be useful to reinterpret past findings in light of this variable.

1.5 The Current State of the Dual-Task Walking Literature

The gait of healthy older adults is negatively affected by dual-task conditions (Smith, Cusack, & Blake, 2016). This is also true in PD, and furthermore, the literature suggests that dual-task costs to gait variability might be exacerbated by PD (Rochester, Galna, Lord, & Burn, 2014; Yogev et al., 2005). The review by Kelly et al. (2012) and meta-analysis by Raffegeau (2019) demonstrated that studies examining PD tend to show strong evidence for reductions in walking variables like speed and stride length in response to a dual task. A problem, however, is that it is common to only report dual-task costs for the walking parameters, ignoring possible analyses on the concurrent cognitive tasks. Without considering changes to the cognitive task, it cannot be known whether an observed motor dual-task cost occurred in tandem with a cognitive cost, with no change to the cognitive task, or with cognitive facilitation—as Plummer and Eskes (2015) state, having this full picture of the results is necessary to properly interpret the degree of cognitive-motor interference. Their argument is reminiscent of Norman and Bobrow's (1975) chapter in which the point is made that speed-accuracy tradeoffs can appear different depending on whether speed and accuracy are positively or negatively correlated.

Of the few studies who have reported a more detailed cognitive profile of their PD sample, Stegemöller et al. (2014) administered a battery of tests prior to dual-task walking and grouped scores into three factors; namely, processing speed, executive function and attention, and working memory. Stegemöller et al. used reflective markers and motion capture to measure dual-task walking while participants (n = 35 individuals with PD) performed serial-3 subtractions. Although cognitive dual-task costs were not

explicitly reported, significant dual-task costs were found for a variety of spatiotemporal gait measures—walking velocity, stride length, step width, stride time, and swing time—as well as significant costs on measures of gait variability (calculated by using coefficient of variation)—step width variability, stride time variability, and swing time variability. Furthermore, correlation analyses suggested a relationship between processing speed and the spatiotemporal variables of stride length and velocity, while step width and step width variability, which are instead reflective of gait stability, were associated with executive function and attention. Finally, block regression models were then used to test whether gait variables could predict cognitive performance in the authors' three selected domains of processing speed, executive function and attention, and working memory. In these analyses, spatiotemporal walking factors as well as walking variability factors were able to explain variance in processing speed and executive function, but not working memory.

Although Stegemöller et al.'s (2014) work was an important step forward, their study has several limitations that require attention. First, because this was the first study to use a large battery of cognitive variables in this manner and because not all of their variables mapped cleanly onto their proposed dichotomy of temporal vs. postural walking, future work should attempt to confirm these results using a different but related set of tasks. Secondly, the authors did not report or analyze cognitive dual-task costs, or even directly analyze the cognitive data beyond creating the factors to be used in the prediction models. The regular cognitive data would also need to be analyzed, because while dual-task costs themselves offer one form of information, they are relative and thus obscure any potential patterns or differences in the absolute data (Plummer & Eskes, 2015). For example, an individual with a mean velocity of 70 cm/s may have the same

dual-task cost values as an individual with a mean velocity of 130 cm/s; these individuals would not differ only if dual-task costs were considered, but their absolute differences should not be ignored. Stegemöller et al. also did not include a control group or counterbalance their single- and dual-task walking trials. Finally, these findings are based on using gait variables to predict scores on cognitive variables. However, because the relationship between cognition and walking is not necessarily unidirectional, future studies should also examine the ability of performance on the cognitive tasks to predict variance in gait performance.

Gaßner et al. (2017), in contrast to Stegemöller et al. (2014), failed to find much support for a link between dual-task walking costs and cognitive ability in PD. Again, Gaßner et al.'s goal was to predict cognitive function (in this case, cognitive impairment as established based on a cutoff score of 26 on the Montreal Cognitive Assessment, MoCA) from the dual-task effects on gait, and thus used correlation and regression analyses to examine the relationship between MoCA score and dual-task costs to the various gait variables. Dual-task costs to stride length, swing time variability, and maximum toe clearance while performing serial-3 subtractions were only able to explain 8.6% of the variance in MoCA score, a number which Gaßner et al. considered small. Stegemöller et al.'s single-task walking factors explained 7.31% of the variability in processing speed, and adding the dual-task costs explained an additional 11.03%. Gaßner et al.'s relatively null results may, however, have been due to a number of limitations. First, they used a serial three subtraction task as the concurrent cognitive task, for which they did not calculate cognitive dual-task costs, a metric essential to data interpretation. A simple explanation that cannot be ruled out for both Stegemöller et al. and Gaßner et al. is

that their concurrent cognitive task, counting backwards by three, was not sufficiently challenging for participants. It also does not easily allow for the calculation of a cognitive dual-task cost (accuracy must be scored manually, and speed of completing the task has a strange interpretation because it is not a classical response time). Moreover, regarding cognitive impairment in the sample, the only cognitive assessment task used in the study was the MoCA (Nasreddine et al., 2005). A relatively short test such as the MoCA may not have the same discriminatory potential of computer-based tasks that contain many more trials (and therefore have greater statistical power) and which allow for the collection of response times in addition to accuracy. As a general measure of cognition, it also does not tax attention and executive control to the same degree as a domain-specific battery. The question of the role of attention in Parkinson's disease is therefore still unanswered.

More recently, the study of Penko et al. (2018) contributed to the literature on the role of cognition in dual-task walking, although their cognitive measures were primarily based on response accuracy and thus did not incorporate response time. Their study compared dual-task effects from a variety of concurrent cognitive tasks on gait variables, concluding, perhaps surprisingly, that there were no differences between single- and dual-task performance on any of the cognitive measures (*n*-back with levels $n = 0$, 1, and 2; serial 7 subtraction; digit recall; controlled oral word association; and the Stroop task). Two particularly noteworthy findings were that velocity decreased significantly with all of the cognitive tasks, and that dual-task costs to gait were observed at all levels of the *n*-back task. As Penko et al. suggest, their data support a limited resource hypothesis, given the ubiquity of dual-task deficits across all cognitive tasks.

1.6 Summary

People with PD have both motor and cognitive symptoms. The cognitive symptoms, which affect a large proportion of people with PD and are seen as a research priority, can negatively affect motor function. Although recent studies have begun to unravel the cognitive underpinnings of cognitive-motor interference and dual-task effects on walking, few studies have reported thorough investigations of the cognitive contributions to walking. Design limitations and impoverished reporting of cognitive data (relative to walking data) suggest a need for further investigation. While motor dual-task costs are virtually uncontested in the PD data, more could be done to better understand how different tasks might affect the costs in different ways, and how both accuracy and reaction time scores on cognitive tests might be considered with respect to dual-task performance. Achieving these research goals may help interpret the degree to which the findings of studies like Stegemöller et al. (2014) and Gaßner et al. (2017) are due to the tasks chosen vs. underlying cognitive and motor ability.

1.8 Purpose

The primary purpose of this study was to examine the effect of attention and working memory on cognitive-motor interference using a dual-task walking paradigm in PD with a healthy, matched control group. A secondary purpose was to establish whether the pacing of the concurrent cognitive task may affect the pattern of results obtained.

1.9 Research Questions and Hypotheses

This study had four main research questions.

1. Do people with PD and healthy, matched controls differ with respect to cognitive performance across a broad group of tasks designed to measure components of attention and working memory? We hypothesized that the PD group would show deficits relative to controls across all tested domains. Specifically, we predicted the PD group would have slowed response times (RT) and decreased accuracy across the measures, as well as worse performance on the components of attention (i.e., the composite scores from combining tests into factors such as vigilance and executive function).

2. Does walking—assessed through the gait variables of velocity, stride length, cycle time, and double support—differ between individuals with PD and healthy controls? We predicted that the PD group would have deficits on both the spatiotemporal variables (slower velocity and cycle time, and shorter stride length) and postural variables (more time spent in double support and greater variability, as measured by coefficient of variation, across all gait variables).

3. Are people with PD affected differently by the addition of a dual task than healthy controls? We hypothesized that the PD and control groups would show dual-task costs on both the gait and cognitive variables, but that the PD group would show greater dual-task costs than controls, particularly for gait variability and cognition. Furthermore, within these dual-task effects, would the pattern of results differ depending on the pacing of the cognitive tasks? We predicted that dual-task costs would be lower with the self-paced version of the cognitive task because participants could slow down and/or temporarily ignore the cognitive task as needed to maintain accurate performance on both

tasks. We therefore predicted that response times would be slower in the self-paced condition, but that accuracy would be higher.

4. Which domains of attention and working memory, if any, predict single walking and dual-task effects on walking in PD? We hypothesized that our vigilance network of attention, which is similar to Stegemöller et al. (2014)'s processing speed factor, would be associated with single walking performance, and that executive control and working memory (despite Stegemöller et al.'s lack of findings with working memory) would best predict variance in dual-task effects due to their roles in task switching and information processing capacity.

Chapter 2: Method

2.1 Participants

A total of 30 participants aged 50 and older completed this study: 15 had a diagnosis of PD and 15 were healthy controls matched as closely as possible for general cognitive ability, age, sex, and education. Participants were screened on the basis of the following inclusion criteria: aged 50 and older, able to walk unassisted for at least 300 meters, normal or corrected-to-normal vision and hearing, and, for the PD group, participants must have been in the ON phase of their medication (i.e., if the effects of participants' medication tended to lapse after a certain period between doses, they were tested during the time before the lapse occurred). Exclusion criteria were a history of neurological disease other than PD, physical problems/inability to hear or respond to study stimuli or complete the walking procedure, and completion of any of the study measures within the past six months (e.g., as part of another study).

Participants were recruited through events such as the Halifax Parkinson SuperWalk and the 2019 Parkinson Canada Mind Over Matter conference hosted in Halifax, visits to Parkinson Canada-affiliated support groups across Nova Scotia, as well as word of mouth and posters displayed in the community. Posters were also circulated by employees of Parkinson Canada in person and on Parkinson Canada's locally-focused social media. The resulting sample was therefore quite geographically diverse within Nova Scotia, with approximately half of the participants commuting from outside the Halifax Regional Municipality.

It is noteworthy that six couples participated in the study. Five were PD–control couples, while both members of the other couple were in the control group. Although this

cohort (n = 12 individuals) was too small to incorporate any clustering into the analyses (e.g., of individuals nested within couples), it is hoped that they will improve the overall study control on lifestyle/environmental factors such as diet and sleep.

Variables describing the sample and matching are presented in Table 1. Welch's t-tests were performed to screen for baseline differences in the variables listed in Table 1. Only education differed significantly between groups, with the PD group having roughly 1.5 additional years of education, Welch's $t(27.98) = 2.20$, $p < .05$, $d = 0.81$, 95% CI [0.12, 3.15]. All participants with PD but one were taking medication for their motor symptoms (Levodopa/Carbidopa), and one person had received deep-brain stimulation. The amount of time between MDS-UPDRS III administration and the PD group's last dose of Levodopa/Carbidopa was not correlated with MDS-UPDRS III score, Spearman's $r_s = .23$, $p = .44$, suggesting that differences in motor performance could not be explained by differences in medication timing.

All participants provided informed consent prior to participation.

2.2 Research Design

This was a mixed-measures, cross-sectional study with a nonrandomized between-subject factor of group (PD vs. healthy control) and within-subject factors of repeated measures, task type, and task complexity.

2.3 Cognitive Profiling Measures

2.3.1 Trail Making Test

The Trail Making Test (TMT) is a common neuropsychological test that can measure both executive function and processing speed (Tombaugh, 2004). It involves two parts, A and B. In the former, participants must connect numbered circles in ascending order as quickly as possible, and in the latter, participants alternate between an ascending sequence of numbers and an ascending sequence of letters (i.e., 1–A–2–B–3 …). The final score on both parts is time (seconds) until completion. Errors are accounted for in the time score because the experimenter stops the participant (but not the timer) whenever they make an error and they must go back to the last correctly-completed circle and continue the task from there.

2.3.2 Montreal Cognitive Assessment

The MoCA (Nasreddine et al., 2005; www.mocatest.org) is a short test that requires both paper-and-pencil and oral responses, and is designed to screen for general cognitive ability. The final score is a number out of 30, with lower scores suggesting potential problems with cognition or mild cognitive impairment (note that cutoffs are debatable; see Rossetti, Lacritz, Cullum, & Weiner, 2011). We used the MoCA to compare the general cognitive abilities of the groups.

2.3.3 Dalhousie Computerized Attention Battery

The Dalhousie Computerized Attention Battery (DalCAB) is a series of computerized tests designed to measure the three attention networks of vigilance, orienting, and executive control (Jones et al., 2015; Petersen & Posner, 2012; Posner & Petersen, 1990). Performance on the DalCAB has been shown to have good to very good

reliability, and each component of the battery has demonstrated response patterns or effects established in the literature, such as effects of task switching and response inhibition (Jones et al., 2016).

Performance on the DalCAB subtests is quantified by accuracy (correct responses to stimuli) and reaction time (speed of response to a stimulus). In this study, we used six subtests of the DalCAB to quantify vigilance, executive control, and working memory abilities. The subtests, for which details are available in Jones et al. (2015), are as follows: simple response time (a vigilance task in which one makes a one-button response to the appearance of a single visual stimulus), choice response time (a vigilance task in which one responds to the appearance of one of two targets, using a separate button for each target), go/no-go (an executive task in which a single-button response is made to one of two possible stimuli; the other stimulus must be ignored), dual task (an executive task in which the choice response time task described above is paired with counting the number of each of the two targets, followed by recall of a randomly selected target), vertical flanker (an executive task in which a response must be made based on the identity of the centre shape in a column of five congruent or incongruent distractor shapes), and item memory (a working memory task in which a series of objects are shown, after which a response is made to indicate whether a probe that follows the series was or was not part of the sequence). For the purposes of this study, we collapsed across trials with variable stimulus-response intervals in the simplest response time task, and also collapsed across set sizes on item memory, which could vary between two and six. Within-subjects variables of interest from the other tasks included target rate on go/no-go (20% vs. 80% targets), switch vs. no-switch trials on the dual task (i.e., for the choice

response time portion of the dual task, each presented stimulus could be the same as or different from the one last presented), and congruency of the distractor stimuli with the target on vertical flanker.

To reduce the duration of session one, we used the short version of the DalCAB, which has half the number of trials in each task as the original DalCAB publications (Jones et al., 2016, 2015).

2.3.4 Radar Watch

Radar Watch is a game-like vigilance assessment and training tool developed by the Eskes Lab (publication forthcoming). In Radar Watch, the player monitors a circular radar sweep, looking for specific target objects. Final scores are based on average accuracy (% target hits – % false alarms) and response time. We used Radar Watch to measure goal neglect, an executive aspect of vigilance characterized by participants' failure to switch targets following a cue to do so despite their explicit knowledge of the task instructions (Duncan, Emslie, Williams, Johnson, & Freer, 1996; Duncan et al., 2008). In Radar Watch, participants begin responding to one target and will either switch once or not at all during the course of a block of 17 radar sweeps (trials). Both the current target and a second object (which will become the next target if the block is a switching block) are visible from the start of the block; goal neglect is thus measured by observing changes to accuracy and reaction time following a target switch, which is cued by a flash of colour associated with the other target. To ensure an even comparison, we compared mean performance on the five trials immediately following a switch (trials 12–17 of the 17-trial block) to mean performance on the same five trials (12–17) in blocks without a switch.

2.4 Concurrent Cognitive Task

2.4.1 Auditory *N*-Back

We used an auditory *n*-back task developed in our lab as the cognitive task to be performed concurrently with walking. In this version of the task, participants listened to a sequence of letter stimuli and made a two-choice button response to indicate whether the current letter heard was the same as or different to the letter presented *n* times ago; a response was thus required for every trial after the first *n* trials. Participants performed at a level of $n = 1$ while learning the task and at a level of $n = 2$ during the dual-task walking trials, except for one individual in the PD group for whom $n = 2$ was too challenging (the participant could not demonstrate understanding of the task to the researcher and was unable to perform the task above chance level after several practice blocks). This individual performed at a level of $n = 1$ throughout the study. *N*-back was selected for its ease in providing a controlled manipulation of pacing, as well as its demands on attention and working memory (Gajewski, Hanisch, Falkenstein, Thönes, & Wascher, 2018).

The *n*-back task was played in two modes: fixed-paced and self-paced. In the fixed-paced mode, participants heard a new letter in the sequence every three seconds, including the time to play the letter sound, regardless of whether and when an input was made. In the self-paced mode, participants heard a new letter 200 ms after they pressed the button indicating whether the letter was a match or not (the first *n* responses do not have a "match" or "non-match" value, so they were discarded). The self-paced mode could thus advance as quickly or as slowly as participants desired, and letters could be heard at a faster rate given the smaller stimulus-response interval of 200 ms.

Because participants walked for a fixed number of passes (six per condition) on the GAITRite mat, the number of *n*-back trials completed during walking varied for each participant, given differences in walking and turning speed. To assess this variability, we performed a 2 x 2 ANOVA on the number of completed trials (including correct and incorrect trials) with pacing (fixed or self) as the within-subjects factor and group (PD or control) as the between-subjects factor. The PD group (M_{fixed} = 24.9, M_{self} = 40.4) performed significantly more trials than the control group (M_{fixed} = 20.6, M_{self} = 34.8), as evidenced by a main effect. There was also a main effect of pacing, whereby more trials were completed during self-paced *n*-back. There was no interaction, however, suggesting that the difference between pacing modes did not vary as a function of PD. We opted to fix the number of passes on the mat, rather than the number of *n*-back trials, in order to strike a consistent balance between maximizing power and not physically overtaxing participants. During single-task *n*-back, all participants completed 52 trials (20 matches, 20 non-matches, and 12 foils/near matches). Participants completed significantly more *n*-back trials during walking with the self-paced *n*-back (M = 37.6, SD = 8.3) than walking with the fixed-paced *n*-back (M = 22.7, SD = 7.9), $t(59) = 16.6$, $p < .001$, $d = 2.14$, 95% CI [13.1, 16.7].

2.5 Walking Measures

2.5.1 GAITRite®

Walking data were collected using a 5.7 meter-long GAITRite® mat in suspended walks mode. Participants walked continuously back and forth without interrupting their pace—to ensure the GAITRite had enough time to reset between passes, participants took several steps off the mat in each direction (lines were marked with green tape a few steps away to serve as a reminder) before turning and continuing.

2.5.2 Dual-Task Walking

Dual-task walking was measured by having participants walk along the GAITRite mat while performing the auditory *n*-back task simultaneously. Participants were instructed to begin walking as soon as they heard the first letter in the *n*-back task. Letter stimuli were delivered through a Logitech® G930 wireless gaming headset; participants made responses using a Logitech® G900 Chaos Spectrum gaming mouse secured to their dominant hand with Fabrifoam MediWrap (https://www.fabrifoam.com/). Gaming peripherals were chosen to minimize hardware-specific response time latencies; for example, Logitech advertises the mouse's wireless report rate to be 1000 Hz/1 ms (Logitech G, n.d.). Further to this goal, responses were collected on a computer running the Windows System Timer Tool (Version 3; Halm, 2015), which allowed us to set the system refresh rate to 0.5 ms (i.e., to receive inputs from the mouse at a more accurate rate than the system default of checking every 15 ms).

Participants walked for six passes in each condition (i.e., single walking, walking while performing the fixed-paced version of the *n*-back, and walking while performing the self-paced *n*-back), followed by another six passes of each condition in reverse order

to ensure single walking occurred at the beginning and end of the gait data collection phase (to minimize order effects). In total, therefore, 12 passes of 5.7 meters each were obtained for each condition, per participant.

2.6 Questionnaires

2.6.1 Study-Specific Questionnaires

In addition to their health history and background, we administered a screening form (Appendix A) which inquired about general factors that might affect participants' performance in the study. The screening form included questions about computer and gaming experience, level of physical activity, walking difficulty, and recent falls. This was used to help with matching and to describe the sample (Table 1).

We also created and implemented a brief exit questionnaire (Appendix B) that asked participants about their experience (difficulty and engagement) with the cognitive and gait measures in the study. This was primarily to obtain feedback on our software, but also to ask participants about the extent to which they may have prioritized either the cognitive or motor task during dual-task walking.

2.6.2 MDS-UPDRS Section III

We administered Section III of the Movement Disorder Society-sponsored revision of the Unified Parkinson's Disease Rating Scale (MDS-UPDRS; Goetz et al., 2008) to individuals in the PD group in order to quantify their progression of motor symptoms. The final score on the MDS-UPDRS is a sum of ratings across individual items assessing motor functions such as rigidity, dyskinesias, gait, and postural stability. The range of scores on the UPDRS-III from Raffegeau et al.'s (2019) meta-analysis of

dual-task walking studies in PD was 14.4–39.2 with an unweighted mean and standard deviation of 22.7 and 6.3; our sample had a mean of 29.27 and a standard deviation of 10.68.

2.6.3 Dual-Task Activity Questionnaire

In the Dual-Task Activity Questionnaire (Plummer, Giuliani, Feld, & Zukowski, n.d.; based on Tun & Wingfield, 1995), participants are presented with a variety of real-life dual tasking scenarios, which they must rate for difficulty (1–5; very easy to very difficult) and frequency (0–2; not at all or less than once per month to more than six times per week). Final scores for difficulty and frequency are the sum of ratings for all items, with higher scores indicating greater difficulty (range of possible scores = 28–140) and more frequent dual tasking (range of possible scores = 0–56).

In cases in which participants did not do the activities in question, they were asked to imagine themselves combining the two in order to provide a rating. This mostly occurred for a few individuals who used to drive but no longer had their driver's license; hence, the frequency was reported as 0 but the difficulty was reported based on imagining themselves doing the activity in the present.

2.7 Procedure

The procedure for the study is presented as a flow chart in Figure 1. Everyone in the study completed the same tasks, with the exception of the MDS-UPDRS III, which was unique to the PD group. The study took place on two separate days to minimize fatigue: session one took approximately 2.5 hours and involved consent, screening, and the cognitive measures (TMT, MoCA, DalCAB, Radar Watch, and learning/practicing

the auditory *n*-back). The order of tasks in session one was fixed. Participants were given time to learn/practice the auditory *n*-back at the end of the first session. We did not use these data in our analyses, but provided this time because our goal was to specifically measure the effects of combining the *n*-back with walking, not individual differences in learning the *n*-back task (which could confound the data needed to answer our question).

Session two took approximately 1.5 hours and involved single- and dual-task walking trials, followed by the MDS-UPDRS Section III (for the PD group), the Dual-Task Activity Questionnaire, and the study exit questionnaire. To avoid practice or order effects that could arise between the single- and dual-task walking blocks, we used Fraser, Elliott, de Bruin, Bherer, and Dumoulin's (2014) counterbalancing scheme. All participants thus completed fixed-paced single *n*-back, self-paced single *n*-back, single walking, fixed-paced dual-task walking, and self-paced dual-task walking, and then repeated each condition in reverse order (i.e., fixed-paced single *n*-back occurs first and last, self-paced dual-task walking occurs back-to-back at the end of the first round and the beginning of the second round, etc.). We did not give participants any instructions regarding the prioritization of the motor or cognitive task, as such instructions have been shown to affect performance (Kelly et al., 2012; Yogev-Seligmann et al., 2010)

Sessions were scheduled during times in which people with PD would be in their ON phase for as long as possible (or, in the case of controls, during times that people with PD had already selected in order to improve control group matching). Participants were offered breaks between tasks as needed.

Chapter 3: Results

All analyses were performed using jamovi (Version 1.0.5.0; The jamovi Project, 2019), unless otherwise stated. Analysis programs were run on macOS version 10.14.5 (Mojave).

3.1 Data Cleaning

3.1.1 GAITRite Data

Two types of errors affected data acquisition on the GAITRite mat, albeit rarely. First, some passes across the mat could not be processed by the system, because the footfalls failed to register properly. In the second type of error, the footfalls appeared correctly but the numbers did not make sense (e.g., negative values for step length). We inspected the data from all passes and removed nonsensical values from the second type of error as well as extreme values found for only one variable in a given data frame. For example, if a participant's typical value for double support was between 30 and 35, but for one pass it was 70, we did not include that data point. These errors were easy to distinguish from natural variation, because in such instances, only one variable would be different for that pass—e.g., double support might change to 70, but the values for velocity, stride length, and even single support (which is expressed as a percentage of the gait cycle along with double support) remained consistent with the data from the other passes. Real changes to double support (or any other variable) would be reflected in at least some changes across the board.

Overall, missing data resulting from both types of errors described above included 5.03% of passes in the PD group and 2.41% of passes for the controls (the decimal

numbers are possible because of the rare occasions in which only a single variable was affected—for example, in the PD group, double support had one more unusable pass than the other variables). We expect there were a greater number of errors in the PD group due to their increased likelihood of shuffling, which may have prevented the wire sensors in the mat from establishing an accurate reading.

Stride length, cycle time, and double support (i.e., all gait variables except velocity) have separate values for the left and right leg. We collapsed left- and right-limb performance into a single score before performing the analyses, given that our research questions were not specifically concerned with symmetry and because gait was highly symmetrical according to a 2 x 2 ANOVA with limb side as the within-subjects factor and group as the between-subjects factor. None of the variables—stride length (M_{left} = 114.66 cm, M_{right} = 114.61 cm), cycle time ($M_{left\ and\ right}$ = 1.15 s), and double support (M_{left} = 27.75, M_{right} = 27.83)—showed significant differences between left and right side, nor were there any interactions with group (all p-values > .1).

3.1.2 Cognitive Data

We only used reaction times from correct trials across all of the measures. This was done to ensure that our conclusions are based on performance reflecting the cognitive process involved in successfully executing the task.

There are two potential bands of response time (RT) outliers: values that are too quick to have involved the decision-making process of interest (i.e., anticipations) and values that are much slower than an individual's typical RT (i.e., more likely to indicate distractions/failure to pay attention or perform the task rather than slow processing).

For all computer tests except self-paced *n*-back (i.e., DalCAB, Radar Watch, and fixed-paced *n*-back), the upper-bound of RT values is constrained by the response time window. For these tasks, a trial ends after a set timeframe has elapsed (usually between one and three seconds; see Table 1 in Jones et al. (2015) for values specific to the DalCAB), and failure to respond on a trial counts as a "miss" (an error)—thus, nothing was done to trim the upper bounds of the data. For the self-paced *n*-back, we explored a potential cut-off threshold of 6000 ms (double the 3000 ms trial window of the fixed-paced *n*-back, which results from a 2500 ms stimulus-response interval plus the time to pronounce each letter). Only 10 trials greater than 6000 ms were present in the entire dataset, and 8 of them were correct trials. Because the intent was to keep as many true trials as possible and because participants may have adopted a posture-first strategy and deliberately taken more time with the cognitive task, we did not remove any upper-bound values for self-paced RT.

Selecting an acceptable lower bound of RT values represents a tradeoff in sensitivity whereby low cutoff thresholds may lead to the inclusion of random responses in the data (due to anticipations) and high cutoff thresholds may fail to capture real scores that were either faster than the experimenter predicted or perhaps resulted from strategies such as prioritization of RT over accuracy in a speed-accuracy tradeoff. Previous testing of the DalCAB in our lab has explored the effects of a variety of potential cutoff values varying with task complexity, finding no change in the pattern of results between 100 ms and 400 ms (Jones et al., 2016; see also Christie, Hilchey, & Klein, 2013). Therefore, to keep as much data as possible and follow the current standard DalCAB procedure (Jones

et al., 2016, 2015), we removed anticipations, defined as trials with RT < 100 ms, for all computerized measures in the study.

We did not adjust any of the values for the Trail Making Test (the only timed paper-pencil task), because no participant took a break in the middle of the test or failed to comply with the instructions; hence, even extremely long times to complete the test are true values.

3.2 Statistical Analyses and Effect Sizes

Throughout this paper, we report two-tailed tests. We used Welch's *t* rather than the Student's *t* for all independent-samples *t*-tests because it performs better when data do not meet the assumption of homogeneity of variance, at little cost to power when the assumptions are met (Delacre, Lakens, & Leys, 2017). Where possible, effect sizes and confidence intervals are provided. Due to their ease of interpretability, we report Cohen's *d* for t-tests and eta squared (η^2) for ANOVAs. When the numerator of the degrees of freedom in the ANOVA test is equal to one, the square root of eta squared is equivalent to *r* (the correlation coefficient), whereas eta squared itself is equivalent to R^2 (i.e., proportion of variance accounted for) when the numerator of the degrees of freedom is greater than one (Levine & Hullett, 2002).

Reaction time and accuracy are the primary variables of interest for the cognitive data. We sometimes report errors instead of accuracy. In these cases, errors are defined as 1 − accuracy and are used to standardize the interpretation of mean differences in both reaction time and accuracy. When errors are used, larger numbers indicate slower and

less accurate performance (i.e., more errors), and smaller numbers indicate faster and more accurate performance.

We report results organized by research question. Some statistical tests on the *n*-back and walking data, however, helped inform more than one research question (e.g., ANOVAs addressed both single walking and dual-task walking). In these cases, we emphasize the effects relevant to the research question of focus (e.g., comparing performance on the cognitive and gait measures themselves in the first two research questions, and then comparing dual-task effects in the third question).

Given the large number of statistical tests in this study, we opted to report most statistical tests in tables, rather than in text, so that the pattern of results could be clearly communicated. Thus, results for measures with only a few *F*-tests are reported in the text (such as the TMT or Radar Watch), whereas measures with large amounts of statistics to report are presented in tables (such as the *n*-back, which has 14 *F*-tests between reaction time and accuracy data). Tables are always separated by relevant factors such as group or task pacing; figures showing the results of tests based on the same data may be collapsed by factors that were not significant in order to better display the significant effects and interactions.

To follow up significant findings in the reported ANOVAs, I used either mean values and/or graphs with confidence intervals, or relevant post-hoc tests, as appropriate. For example, the direction of main effects could easily be established with graphs (e.g., an unambiguous main effect of group in which the PD group always performs worse than the control group), whereas interactions are better decomposed using confidence intervals and/or post-hoc tests.

3.3 Question #1: Effects of PD on Cognition

Our first research question concerned whether differences would arise in single-task cognitive performance between the group with PD and the healthy, matched controls. To address this question, we compared performance between groups on the following measures of cognitive ability: the TMT, the DalCAB, Radar Watch, and the auditory n-back at a level of n = 2. As part of control group matching, there was no difference in general cognitive ability, as measured by the MoCA, between the PD and control groups (see Table 1 for mean values), $t(27.9) = 0.87$, $p = .39$, $d = 0.32$, 95% CI [−0.91, 2.24]. Additionally, according to the Dual-Task Activities Questionnaire (see Table 1 for mean values), there were no differences between the PD and control groups in perceived difficulty of performing dual-task activities, Welch's $t(27.6) = -1.37$, $p = .18$, $d = -0.50$, 95% CI [−21.26, 4.20], nor differences in the frequency with which participants performed dual-task activities, Welch's $t(27.1) = 0.74$, $p = .47$, $d = 0.27$, 95% CI [−3.42, 7.29].

3.3.1 Trail Making Test

As per standardized scoring, we only analyzed time to complete the TMT, which encompasses errors in that participants must restart from the previous circle after making a mistake (i.e., errors increase the time on task).

These data were analyzed using a 2 x 2 ANOVA with the factors of task complexity (TMT Part A and TMT Part B) and group (see Table 2 for means and standard deviations). Controls performed faster overall, $F(1, 28) = 8.07$, $p < .01$, $\eta^2 = .087$ ($M_{control} = 50.96$, $M_{PD} = 77.77$), and Part B took significantly longer than Part A, $F(1, 28)$

= 57.38, $p < .001$, $\eta^2 = .393$ ($M_{\text{part A}} = 35.86$, $M_{\text{part B}} = 92.88$; Figure 2). There was, however, no significant interaction between group and task complexity, $F(1, 28) = 3.97$, $p = .06$, $\eta^2 = .027$.

3.3.2 Radar Watch

We compared RT (ms) and accuracy (% hits – % false alarms) scores on Radar Watch through 2 x 2 mixed ANOVAs, with group as the between-subjects factor and block type (switch or no switch) as the within-subjects factor (see Table 3 for mean scores).

There were no significant effects for RT; i.e., no effects of block type, $F(1, 28) = 0.665$, $p = .42$, $\eta^2 = .006$, or group, $F(1, 28) = 1.69$, $p = .20$, $\eta^2 = .042$, nor an interaction between the two, $F(1, 28) = 0.183$, $p = .67$, $\eta^2 = .002$.

For accuracy, however, switch blocks were significantly less accurate than no-switch blocks, $F(1, 28) = 24.49$, $p < .001$, $\eta^2 = .210$ ($M_{\text{switch}} = 0.75$, $M_{\text{no-switch}} = 0.92$), and the PD group scored significantly lower overall than the control group, $F(1, 28) = 4.45$, $p < .05$, $\eta^2 = .074$ ($M_{\text{PD}} = 0.78$, $M_{\text{control}} = 0.88$), though there was no interaction, $F(1, 28) = 1.48$, $p = .23$, $\eta^2 = .013$ (Figure 3).

3.3.3 Auditory *N*-Back

Although the primary purpose of the auditory *n*-back test was to be used as the concurrent cognitive task for dual-task walking, single-task performance can be compared between groups to enrich our cognitive profiling of the PD group. *N*-back performance (Table 4) was compared through a 2 x 2 x 2 ANOVA (Table 5) with the factors of task (single/while seated vs. dual/while walking), pacing (fixed- vs. self-paced presentation of letter stimuli), and group (PD vs. control). Effects related to group are the

only factors that inform this first research question. Strikingly, the ANOVA revealed no main effects of group in either accuracy or reaction time, nor any interactions involving group.

3.3.4 DalCAB

To examine performance on the DalCAB, we selected a series of variables that, based on Jones et al.'s (2015) factor analysis, have been shown to load onto the factors of vigilance, executive control, and working memory. These variables are described in Table 6; greater detail can be found in Tables 1 and 2 of Jones et al. (2015).

To analyze these data (Table 7), we performed Welch's *t*-tests for each variable, comparing the PD and control groups. In total, only choice response time (M_{PD} = 597 ms, $M_{Control}$ = 510 ms) and item memory errors (M_{PD} = 31.8%, $M_{Control}$ = 15.6%) differed significantly between groups, with the PD group performing worse.

3.3.5 Grouped Attention Scores

Next, we took the DalCAB scores and select scores from other measures (TMT A, TMT B – A, Radar Watch switch errors, and *n*-back performance) that grouped into the attention factors of vigilance, executive control, and working memory. The goal was to explore any potential differences between people with PD and the controls at the network level by creating forest plots similar to those made in meta-analyses. The attention variables in this study are thus analogous to individual research studies in meta-analyses, and our attention factors are analogous to the weighted overall effects. To perform this analysis, we used the Cohen's *d* values from previously reported *t*-tests and computed 95% confidence intervals for each *d* using the following calculations, which require the calculation of variance for Cohen's *d* (Borenstein, Hedges, Higgins, & Rothstein, 2009):

$$V_d = \frac{n_1 + n_2}{n_1 n_2} + \frac{d^2}{n_1 + n_2}$$

$$95\%\ \mathrm{CI} = d\ \pm 1.96\sqrt{V_d}$$

After each *d* and its associated variance were calculated, variables were combined into the three factors (vigilance, executive control, and working memory). The Cohen's *d* and V_d computed for each variable parallels the Cohen's *d* and V_d computed for each study in a meta-analysis. Using the random effects model for meta-analyses described in Borenstein et al. (2009), we generated an overall Cohen's *d* with its own confidence intervals. Forest plots showing the results for each variable and weighted random factor are provided in Figures 6–8. It should be noted that confidence intervals for Cohen's *d* were used to facilitate plotting; these are different from typical confidence intervals of the mean difference in that they are standardized. However, the interpretation is the same; an effect is significant if the confidence interval does not cross 0.

All factor groupings trended towards a PD deficit, but only executive control was significant (Cohen's $d = -0.43$, $p = .0046$). We also computed correlations between the variables within each factor (Tables 8–10). Only the vigilance variables showed a high degree of correlation.

3.3.6 Question #1: Brief Summary

Results often trended towards deficits to the PD group, suggesting (as per our hypothesis) poorer attention performance. However, only executive deficits were significantly different in the network analysis, with the PD group performing just under half a standard deviation worse (Cohen's $d = -0.43$). Furthermore, there were no group differences on single-task (seated) performance of the fixed-paced *n*-back task that would later be used as the concurrent cognitive task during dual-task walking. Overall, there is no clear pattern of differences in the cognitive data—some tasks, such as the TMT, suggest a slowing or processing speed deficit in PD, while other tasks, such as Radar Watch, suggest no speed differences but rather problems making accurate responses.

3.4 Question #2: Effects of PD on Walking

To address our second research question, whether walking performance differed between the two groups, we examined four variables measured using the GAITRite mat: walking velocity (cm/s), stride length (cm), cycle time (s), and double support (% GC). We also examined variability within these gait variables by computing the coefficient of variation (COV; $SD / M * 100\%$) for each. Values for group and each walking condition (single walking, fixed-paced dual-task walking, and self-paced dual-task walking; see Table 11) were compared using linear mixed models fit by restricted maximum likelihood (REML), because it is known to work better for small samples and produce a lower Type I error rate than regular maximum likelihood (ML) models (Luke, 2017; McNeish, 2017). For each model, we report R^2 marginal and R^2 conditional—these are estimates of the variance accounted for by the model fixed factors and the variance

explained by both the fixed and random factors, respectively (Nakagawa & Schielzeth, 2013). Due to the study design, each participant had 12 passes on the GAITRite per condition: six were performed in the first instance of the counterbalancing order and six were performed in the second instance. These analyses were conducted in jamovi using the GAMLj module (Gallucci, 2019).

3.4.1 Spatiotemporal Gait Analysis

First, looking at the spatiotemporal values (i.e., ignoring COV values), the pattern of results across the four gait variables was consistent. In all four cases (one linear mixed model per gait variable), group and walking condition were entered as predictors of the dependent gait variable (i.e., velocity, stride length, cycle time, or double support), with participants as the clustering variable (i.e., the models accounted for the repeated measures—passes on the GAITRite mat—being nested within participants). Random intercepts and slopes were entered for individuals. These random effects (which were treated as correlated to achieve model convergence) led to the best (lowest) AIC indices of model fit, and also make sense experimentally in that we expected and observed baseline differences between individuals (hence, random intercepts) as well as differences in the nature of dual-task effects between individuals (justifying random slopes between walking conditions). Jamovi automatically selected either Kenward-Roger or Satterthwaite approximations for degrees of freedom, both of which have been shown to be appropriate in linear mixed models (Luke, 2017).

Finally, we used simple contrast coding to compare the PD group (coded with a value of 0.5) and control group (coded as −0.5), and Helmert contrasts to compare single walking (0.667) against fixed- and self-paced dual-task walking collapsed together

(−0.333 each), followed by a comparison of both types of dual-task walking (0.5 and −0.5). Aspects of the model not specified in the above can be assumed to have used jamovi defaults unless otherwise specified.

The results of the fixed effect omnibus tests for the four variables are reported in Table 12, and the parameter estimates are given in Table 13. As can be seen from the $R^2_{\text{conditional}}$ values in Table 13, most of the models fit the data very well (with random effects included). Double support had the most variability and the least well-fitting model. The results show a stable pattern: the PD group tended to have slower speeds and more effortful gait, based on significant group effects for velocity ($b = -20.90$) and cycle time (b = 0.149), and trends in stride length and double support. Single walking was characterized by faster walking, longer strides, and less time in double support than dual-task walking, and fixed-paced dual-task walking was in turn characterized by faster walking, longer strides, and less time in double support than walking with the self-paced cognitive task. The data only showed main effects; i.e., there were no interactions between group and the walking conditions.

3.4.2 Gait Variability Analysis

The models run for COV (Table 14) followed the same specifications as the spatiotemporal models, with the exception that COV values did not have repeated measures. Whereas each spatiotemporal variable had 12 data points per walking condition (due to the 12 passes across the mat), COV is calculated based on the mean of the 12 observations and thus only one value per walking condition could be obtained. As a result, there were not enough data points to enter a random slope for walking condition,

as was done in the spatiotemporal analyses. These data also suffer from reduced within-subjects power.

Surprisingly, there were no group differences in gait variability, with the possible exception of stride length (*p*-values are approximations in linear mixed models; while $p = .057$, the 95% confidence interval [0.01, 1.53] suggested significance). Stride length was the only variable for which single walking differed from dual-task walking: single walking had greater variability, although the effect was not particularly large, 95% CI [0.04, 0.70]. Aside from double support, dual-task walking with the fixed-paced task was consistently more variable than dual-task walking with the self-paced task. There was also a single interaction in the dataset: group interacted with the contrast of fixed- vs. self-paced dual-task walking for cycle time. As shown in Figure 10, the PD group had greater variability specifically in the fixed-paced dual-task walking condition.

3.4.3 Question #2: Brief Summary

Walking data were consistent in terms of both within-individual variability, symmetry, and the pattern of results in the spatiotemporal analyses. While the PD group tended to walk slower and spend a greater percentage of their gait cycle in double support, the largest effects were the clear differences between single and dual-task walking, regardless of group. The variability analyses were less robust, likely due to the loss of power inherent in the computation of COV. While group differences were virtually nonexistent for variability and fewer differences were observed for single and dual-task walking, the results support a difference between the fixed- and self-paced

dual-task walking conditions, whereby walking with the fixed-paced *n*-back task was more variable.

3.5 Question #3: Cognitive-Motor Dual-Task Effects

To review the effects of dual tasking and the pacing manipulation on both walking and cognition together, we computed dual-task effects (DTEs; Table 15) using the well-established DTE equation:

$$DTE\ (\%) = \frac{dual - single}{single} * 100\%$$

Some dual-task effect values need to be multiplied by −1 to ensure consistent interpretation of dual-task effects as either costs (negative values) or facilitation (positive values). The standard is to add the −1 to variables for which higher values indicate worse performance (Plummer & Eskes, 2015). In the case of this study, we multiplied reaction time values, cycle time, double support, and all COV values by −1. Although we previously examined the effects of the dual task on the raw data themselves through the planned contrasts in our second research question, the relative measure of dual-task effects will explore response patterns in a slightly different manner. We used 2 x 2 ANOVAs with the within-subjects factor of pacing and between-subjects factor of group for all gait and cognitive DTEs (Table 16).

None of the variables had a significant effect of group, though they all had a main effect of pacing, $p < .05$, in which walking with the self-paced cognitive task led to a greater dual-task cost than walking with a fixed-paced cognitive task, and fixed-paced *n*-back had a greater dual-task cost than self-paced *n*-back. Furthermore, there was an

interaction of pacing and group for double support, in which, according to post-hoc testing, self-paced dual-task costs were significantly greater than fixed-paced dual-task costs in the PD group only, $t(28) = 3.46$, $p = .002$.

We then plotted cognitive and walking DTEs in the format recommended by Plummer and Eskes (2015) in their review of quantifying dual-task effects. This system involves making (x, y) points in a standard, four-quadrant Cartesian plane, wherein the value for x is the cognitive DTE and the value for y is the gait DTE. The quadrant of a data point indicates whether the dual-task facilitated or detracted from performance, while the distance between points is a measure of the difference between dual tasks (in our case, the difference between fixed- and self-paced dual-task walking).

The visualization for velocity using *n*-back accuracy is provided in Figure 11; the plot using *n*-back RT is given in Figure 12. Values fell exclusively in the lower-left quadrant for *n*-back accuracy and velocity, suggesting that the dual task was associated with a cost to both gait and cognition. When *n*-back RT was considered, however, the fixed-paced values were located in the lower-right quadrant, suggesting a cost to velocity, but in the context of a facilitation to RT on the other task. It should be noted that the other gait variables showed a completely identical pattern of results (Appendix C).

3.5.1 Question #3: Brief Summary

The dual-task effects analyses differed from the analyses performed to answer question #2 in that velocity and cycle time no longer had significant effects of group. However, the overwhelming trend was for dual-task effects to be negative values, suggesting a slowing in response to the complex demands. Like the linear mixed model

results, the pacing manipulation was responsible for the most robust differences across the data.

3.6 Question #4: Cognitive Predictors of Single and Dual-Task Walking

The final objective of this project was to determine whether gait patterns in people with PD could be predicted by performance in one or more cognitive domains. For this question, we examined a single gait variable in order to keep the analysis focused. We chose velocity because it showed group effects in the linear mixed model and because of its ubiquity as an outcome measure in the literature (Raffegeau et al., 2019). We included all relevant permutations of velocity; namely, single velocity, fixed-paced dual-task effects (because fixed-paced is the more standard implementation of *n*-back), and the COV of velocity for both single and fixed-paced dual-task effects. Velocity performance reflects spatiotemporal gait, and variability in velocity as measured by the COV values provide a marker of gait stability.

For cognition, we used the factors of vigilance, executive control, and working memory established earlier and graphed in Figures 6–8. To combine the variables that contributed to the domain scores, we computed *z*-scores for each participant (standardizing relative to the entire sample), for each variable. We then averaged the *z*-scores of each relevant variable; for example, the vigilance score was computed as the average of *z*-scores for simple response time, simple response time preparation effect, choice response time, and TMT Part A.

In a similar fashion to Stegemöller et al. (2014) and Gaßner et al. (2017), we computed correlations between our gait variables and cognitive factors (Table 17). This

step was included because in order for a cognitive domain to be able to predict single- and/or dual-task walking ability, then it should be correlated with at least one relevant measure of gait. On the basis of these correlations, our data do suggest a positive relation between cognition and walking: all significant correlations between velocity and attention were positive, and all significant correlations between the COV of velocity and attention were negative.

We next ran hierarchical linear regressions for each type of velocity variable, entering group into step one of the model, and any of the three cognitive factors that correlated with the velocity variable into step two. Thus, executive control was used to predict single velocity (Table 18), vigilance was used to predict the dual-task effects of velocity (Table 19), and both vigilance and executive control were used to predict the COV of single velocity (Table 20). Because no cognitive factors correlated with the dual-task effects of the COV of velocity, we did not run a fourth regression. Our data are unaffected by multicollinearity according to VIF, tolerance, and correlation benchmarks provided by Field (2013).

In the regressions, group was only a significant predictor for single velocity. For cognitive variables, executive control predicted single velocity, accounting for 11.7% of the variance over and above group effects (Figure 13). Vigilance narrowly failed to significantly predict variance in both dual-task effects and the COV of single velocity.

3.6.1 Question #4: Brief Summary

The cognitive domains of vigilance, executive control, and working memory were assessed through correlations to single- and dual-task walking speed and walking speed

variability. This determined the predictors to be used in hierarchical linear regressions, which revealed that executive control predicts single velocity.

Chapter 4: Discussion

The purpose of this study was to build a cognitive and walking profile of a sample of people with Parkinson's disease, and compare their cognitive and walking performance to that of a healthy, matched control group. The goals of the study were to contribute to the literature on cognitive-motor interference using new cognitive tasks during the assessment phase (i.e., Radar Watch and the DalCAB, neither of which had been used in a study of dual-task walking and PD) and a research design that would allow for a controlled comparison of the effect of pacing within a concurrent cognitive task. A further goal of the project was to test whether cognitive performance, when grouped into theoretically-established domains, could predict variance in gait.

Our first research question asked whether cognitive deficits would be apparent in the PD group relative to controls. The forest plots in Figures 6–8 provide a good way to conceptualize the results overall. While the trends are certainly for the PD group to perform worse (for example, the factor of executive control is significant even though none of its constituents are), there are only a few variables that stand out for being strongly in favour of the control group: choice response time, Part A on the TMT, accuracy on the item memory test, and, not included in the forest plots, overall accuracy on Radar Watch (Figure 3). These variables suggest that the PD group is experiencing a general slowing and difficulty with decision speed as well as working memory, although these slowing problems are subtle. This suggests that we succeeded in recruiting people in the early stages of PD, an assertion which is corroborated by the lack of differences on the MoCA and the absence of gait freezes in the dataset. That said, individuals in the PD

group were more educated than the controls, which may partially explain some of our failures to find group differences.

Our second research question concerned walking differences between the PD and control groups. The results, whether significant or trending, were unanimous in supporting the idea that people with PD have poorer gait. It is likely, therefore, that the nonsignificant/trending group effects would be significant with a larger *n* (note that power for the between-subjects effects was relatively low due to the small sample size, whereas power was relatively high for the within-subjects effects due to the many repeated passes on the GAITRite). Moreover, while the PD group did show consistent deficits relative to controls, the overall mechanism of single- and dual-task walking interference appears to be similar in both groups (i.e., using velocity as an example, as seen in Figure 9, both groups followed an exceptionally clear pattern of single walking being fastest, followed by fixed-paced dual-task walking, and finally self-paced dual-task walking). Thus, the differences between fixed- and self-paced dual-task walking are not likely to be specific to PD. This is supported by our findings from our third research question, which examined dual-task effects and concluded that there were no main effects of group. Like the regular walking data, some of those group effects would likely become significant with a larger sample; however, the differences between dual-task costs are not as large as the differences between raw scores themselves (i.e., there was a main effect of group when comparing velocity, but no main effect of group when comparing the dual-task cost itself).

Finally, our attempt to probe relations between attention networks and walking performance led us to several interesting conclusions. First, on the level of correlations,

the three attention factors we computed based on participants' performance on our battery of tasks (vigilance, executive control, and working memory) were all intercorrelated at a level greater than $r_s = .5$. Field (2013) indicates that multicollinearity is not a concern until correlations larger than .8 are observed, but it is nevertheless noteworthy that individuals who performed well in one domain were likely to perform well in the other measured domains. Second, while executive control was a fairly robust predictor of single velocity (predicting 11.7% of the variance), there were no significant predictors of velocity variability or velocity dual-task costs. Additionally, while vigilance trended toward predicting dual-task effects on velocity and single velocity variability, these relationships were the reverse of our expectations. Based on Stegemöller et al.'s (2014) data, we predicted that our vigilance score would be most connected to single walking, while executive control (which should theoretically be involved in the more complicated parts of walking) would instead predict dual-task walking and/or variability, but our data suggest the opposite.

4.1 Contextualized Findings

Throughout our data, the difference between *n*-back pacing modes was unmistakable. We predicted walking with the self-paced *n*-back task would be easier for participants, as they could adopt a posture-first strategy (Belghali, Chastan, Davenne, & Decker, 2017) by delaying processing on the cognitive task without penalty. Surprisingly, the opposite was true—all gait variables showed greater dual-task costs for the self-paced mode, while accuracy was higher on the cognitive task under self-paced conditions. This at least matches participants' self-reported strategies: everyone in the control group

claimed to have prioritized the *n*-back over walking, as did 10 individuals in the PD group—this was also found by Strouwen et al. (2016). The remaining members of the PD group claimed to put equal effort into both the cognitive task and walking, and no one in either group stated that they prioritized walking over the *n*-back. The issue of pacing is complicated and extends beyond RTs themselves: our participants had slower RTs in the self-paced condition but completed almost twice as many trials due to the variable stimulus onset asynchrony between self-paced and fixed-paced blocks. These results suggest that previous studies using self-paced tasks, such as the popular serial subtraction tasks (e.g., as used in Stegemöller et al., 2014 and Gaßner et al., 2017), may overestimate accuracy compared to similar studies employing tasks that require fixed response rates. Our findings also underscore the importance of measuring both accuracy and reaction time—like accounting for cognitive and motor dual-tasks, conclusions cannot be made about the actual effect underlying differences in cognitive performance without the ability to test for speed-accuracy tradeoffs. Although the self-paced task appears more flexible, participants could have—in theory—slowed down the same amount on the fixed-paced version of the task, given that the stimulus-response interval was 2500 ms and RTs did not exceed 1500 ms in either pacing condition (i.e., participants responded fast enough on average to have about a second remaining before receiving the next stimulus). It is possible that mere knowledge of the finite response window (and no explicit knowledge of its duration) created pressure to respond quickly.

Although the findings in this study support the known trend of dual-task costs (e.g., rather than facilitation), as reported in reviews like that of Kelly et al. (2012) and Raffegeau (2019), we, like Stegemöller et al., (2014) and Gaßner et al. (2017), failed to

find a clear predictive relationship between our attention factors and gait. However, our results do contribute to the literature in several important ways. First, we replicated Stegemöller et al.'s (2014) failure to find any significant association between working memory and the gait variables, despite working memory's correlations with the other attention factors. The correlations between working memory and vigilance/executive control suggest that the working memory factor is measuring a related process, but it seems from the gait results that it is not involved in dual-task walking. This is surprising, and may hold implications for researchers looking to investigate the potential effects of working memory training on dual-task interference. Although dual-task training in general has shown promise for improving walking in Parkinson's disease and older adults (Fernandes, Rocha, Santos, & Tavares, 2015; Wollesen & Voelcker-Rehage, 2014), specific working memory training may not be the best choice. Second, the strong relationship between executive control and single velocity suggests that higher order functions may be associated with walking, even if the walking itself does not have a clear link to cognitive processing (as in dual-task walking). The differences in task pacing further suggest that walking is affected by the demands and speed of the cognitive task one is performing concurrently with walking. In the real world, it is likely that the speed demands of the cognitive task contribute, to at least some degree, to dual-task walking safety. For theories of cognitive-motor interference, for which the current literature is undecided between parallel or sequential processing (Plummer & Eskes, 2015), the literature still needs more information. In order to determine whether systems share a limited capacity, the full range of processing over the candidate network needs to be examined (Norman & Bobrow, 1975).

4.2 Limitations

Ideally, the DalCAB analyses would have better accounted for stimulus set sizes. For example, in item memory, as explained by Jones et al. (2015), participants are presented with a random series of objects to remember. Two, four, or six objects can be presented before the participant is asked to recall. It would be logical to assume that response times and accuracy would worsen as the number of objects in a set increases, because more comparisons must be made in order to determine whether there is a match (between the probe and the other items) and more objects need to be held in memory. However, we could not analyze slopes unambiguously in this study, because many people with PD exhibited peculiar response patterns, such as a worsening in speed and accuracy performance but only for the middle set size, or even better performance as a function of increasing set size. In order to perform the forest plot and attention factor analyses, the researcher must know whether larger or smaller numbers indicate better or worse performance. The idea of a smaller set size slope indicating better performance (i.e., individuals adapting to the larger working memory load with less difficulty) only holds in datasets where each individual's performance follows a linear decrease as a function of increasing set size. Future work should find a way to include these variables when this issue occurs.

We chose to use a wireless gaming mouse as an input device given its advertised low-latency polling, and based on personal communication with collaborators who had tried voice-operated relays and found them to unreliably record responses. Most participants, however, disliked having to press two buttons with the same hand, and often made unintentional clicks. The mediwrap used during dual-task walking was only able to

mitigate this to an extent. Participants who struggled the most were allowed to hold the mouse with two hands and respond with both thumbs. We recommend future work use a contemporary game console controller (e.g., Nintendo Switch or XBox controller), which should retain the advantage of low response latencies while allowing for participants to respond comfortably with two hands, using the left and right trigger buttons.

Many participants in both groups reported fear of cognitive decline and/or onset of dementia during testing. The majority reacted viscerally to any error, even when overall accuracy was excellent (e.g., 90% or better). We suspect, therefore, that the data are biased in favour of accuracy over response time. Future work should consider incorporating a means of measuring such response biases.

4.3 Future directions

Future work should continue to investigate how gait might be predicted from cognitive variables by using different tasks to measure the same domains of attention. To minimize the study duration, we did not explore the Posner and Petersen (1990) network of orienting; however, it should be included in future investigations. If time is a concern for future test sessions, working memory tasks could be abandoned on the basis of data from this study as well as that of others (e.g., Stegemöller et al., 2014). Future research could also apply the task pacing findings from this study in a retrospective review of different types of concurrent cognitive-motor dual-tasks.

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Table 1

Descriptive Variables

Variable	Units	PD	Control
Age (years)	*M* (*SD*)	68.47 (6.75)	67.40 (10.00)
Education (years)	*M* (*SD*)	16.33 (2.06)	14.70 (2.00)*
Sex	Male : Female	9:6	5:10
Handedness	Right : Left	13:2	15:0
Health	*M* (*SD*)	3.60 (0.91)	3.73 (0.88)
MoCA	*M* (*SD*)	26.07 (2.05)	26.73 (2.15)
DTAQ Difficulty	*M* (*SD*)	70.4 (16)	78.9 (18)
DTAQ Frequency	*M* (*SD*)	33.7 (7.77)	31.8 (6.46)
Computer hrs/week	*M* (*SD*)	12.30 (13.43)	19.60 (14.55)
Gaming hrs/week	*M* (*SD*)	0.90 (1.73)	2.67 (3.17)
Physical Activity hrs/week	*M* (*SD*)	13.77 (8.52)	14.23 (10.46)
Walking Difficulty	Yes/Sometimes/No	4/3/8	0/3/12
Recent Fall	Yes/Almost/No	11/1/3	7/2/6
Years since PD Diagnosis	*M* (*SD*)	5.33 (4.58)	—
MDS-UPDRS III	*M* (*SD*)	29.27 (10.68)	—
Minutes between last Levodopa Dose and MDS-UPDRS III	*M* (*SD*)	183.14 (108.01)	—

Note. * $p < .05$. DTAQ = Dual-Task Activity Questionnaire. MDS-UPDRS III = Movement-Disorder Society Sponsored Revision of the Unified Parkinson's Disease Rating Scale. MoCA score is out of 30. Health was rated on a 1–5 scale, with 1 indicating "poor health" and 5 indicating "excellent health". The number of minutes between participants' last Levodopa dose was not correlated with MDS-UPDRS III score, Spearman's $r_s = .23$, $p = .44$.

Table 2

Means and Standard Deviations on the Trail Making Test

	PD	Control
TMT A	41.8 (16.0)	29.9 (8.30)
TMT B	114 (59.1)	72.0 (23.6)
TMT B – A	72.0 (53.5)	42.0 (23.2)

Note. TMT = Trail Making Test. Errors are taken into account by the way in which they increase RT.

Table 3

Means and Standard Deviations on Radar Watch

	PD	Control
Reaction Time (ms)		
No-Switch block	626 (56.9)	599 (58.0)
Switch block	631(62.8)	612 (47.3)
Accuracy (% hits − % false alarr		
No-Switch block	0.89 (0.13)	0.94 (0.07)
Switch block	0.68 (0.24)	0.82 (0.13)

Table 4

Means and Standard Deviations on the 2-Back

		PD	Control
Fixed-Paced	Single RT	1094 (177)	1086 (177)
	Dual RT	1126 (195)	1109 (278)
	Single Accuracy	0.80 (0.12)	0.81 (0.11)
	Dual Accuracy	0.72 (0.10)	0.73 (0.13)
Self-Paced	Single RT	1276 (308)	1333 (438)
	Dual RT	1253 (326)	1232 (326)
	Single Accuracy	0.79 (0.09)	0.82 (0.09)
	Dual Accuracy	0.76 (0.12)	0.78 (0.09)

Note. Accuracy was calculated as the percentage of correct responses (i.e., correct match and no-match judgments).

Table 5

Results of the 2 x 2 x 2 ANOVA Exploring N-Back Performance

		F	*p*	η^2
RT	Group	0.0008	.978	< .001
	Task	0.26	.613	.001
	Pacing	14.35	< .001	.083
	Group*Task	0.44	.512	.001
	Group*Pacing	0.12	.735	.001
	Task*Pacing	5.31	.029	.006
	Group*Task*Pacing	0.80	.379	.001
Accuracy	Group	0.27	.607	.007
	Task	66.32	< .001	.076
	Pacing	4.47	.044	.014
	Group*Task	0.01	.908	< .001
	Group*Pacing	0.65	.428	.002
	Task*Pacing	6.93	.014	.010
	Group*Task*Pacing	0.003	.958	< .001

Note. Each *F* had degrees of freedom of 1, 28.

Table 6

Description of Chosen DalCAB Variables

Variable		Description
Vigilance	Simple Response Time	Press a button in response to a single stimulus
	SRT Preparation Effect	The difference in response time to stimuli with an SRI of 500 − 1500
	Choice Response Time	Press one of two buttons in response to one of two stimuli
Executive Control	DT Switch Cost (RT)[a]	Choice response time while also counting the number of each type of stimuli that appeared
	Flanker Int. (Error)[b]	Number of errors on incongruent flanker trials − number of errors on congruent trials
	Flanker Int. (RT)	Response time on incongruent flanker trials − response time on congruent trials
	GNG RT (20% TR)[c]	Response time to go/no-go trials with a 20% target rate
	GNG RT (80% TR)	Response time to go/no-go trials with an 80% target rate
Working Memory	Item Memory (Error)[d]	Number of errors on the item memory task across all set sizes
	Item Memory (RT)	Response time on the item memory task across all set sizes

Note. DT = dual task. Flanker Int. = Flanker interference. GNG = go/no-go. RT = reaction time. SRI = stimulus-response interval. SRT = simple response time. TR = target rate.

[a]In dual task, participants perform choice response time while counting how many times each of the two stimuli appeared.

[b]Flanker is a choice response time exercise in which the target stimulus is the centre of a column of four congruent (same stimulus) or incongruent (different stimuli) distractors (two above and two below).

[c]Go/no-go involves making a response to one type of stimulus while avoiding responses to another stimulus.

[d]In item memory, participants are shown of set of stimuli (either two, four, or six) followed by a probe stimulus. They must indicate whether the probe was or was not part of the set.

Table 7

Performance on the DalCAB

		M (*SD*)					95% CI (Cohen's *d*)	
		PD	Control	*t*	*p*	*d*	Lower	Upper
Vigilance	Simple Response Time	369 (68.9)	387 (98.6)	0.578	.568	0.211	−0.507	0.929
	SRT Preparation Effect	66.1(72.5)	46.9 (56.7)	−0.808	.426	−0.295	−1.015	0.425
	Choice Response Time	597 (93.6)	510 (64.9)	−2.962	.007	−1.081	−1.848	−0.315
Executive Control	DT Switch Cost (RT)	132 (81.0)	160 (90.1)	0.888	.382	0.324	−0.396	1.045
	Flanker Int. (Error)	0.048 (0.072)	0.019 (0.033)	−1.395	.179	−0.509	−1.237	0.218
	Flanker Int. (RT)	74.2 (54.6)	68.7 (47.3)	−0.297	.769	−0.108	−0.824	0.608
	GNG RT (20% TR)	413 (47.4)	383 (39.3)	−1.885	.070	−0.688	−1.425	0.048
	GNG RT (80% TR)	396 (62.5)	364 (36.1)	−1.740	.096	−0.635	−1.369	0.098
Working Memory	Item Memory (Error)	0.318 (0.201)	0.156 (0.087)	−2.872	.010	−1.049	−1.812	−0.285
	Item Memory (RT)	1323 (399)	1214 (240)	−0.907	.374	−0.331	−1.052	0.389

Note. DT = dual task. Flanker Int. = Flanker interference. GNG = go/no-go. RT = reaction time. SRT = simple response time. TR = target rate. Accuracy is expressed here as number of error trials (rather than correct trials) to keep the interpretation direction the same as RT (higher values are worse).

Table 8

Spearman's r_s Matrix for Vigilance Variables

	Simple Response Time	SRT Preparation Effect	Choice Response Time	TMT A
Simple Response Time	–			
SRT Preparation Effect	0.399*	–		
Choice Response Time	0.420*	0.411*	–	
TMT A	0.421*	0.310	0.393*	–

Note. * $p < .05$. TMT = Trail Making Test.

Table 9

Spearman's r_s Matrix for Executive Control Variables

	DT Switch Cost (RT)	Flanker Int. (Error)	Flanker Int. (RT)	GNG RT (20% TR)	GNG RT (80% TR)	TMT B – A	RW Switch Errors
DT Switch Cost (RT)	–						
Flanker Int. (Error)	0.094	–					
Flanker Int. (RT)	0.090	-0.267	–				
GNG RT (20% TR)	0.068	0.286	-0.160	–			
GNG RT (80% TR)	-0.179	0.122	-0.184	0.754***	–		
TMT B – A	0.025	0.292	0.248	0.211	0.122	–	
RW Switch Errors	-0.028	0.336	0.038	0.281	0.154	0.534**	–

Note. ** $p < .01$. *** $p < .001$. DT = dual task. Flanker Int. = Flanker interference. GNG = go/no-go. RT = reaction time. SRT = simple response time. TR = target rate.

Table 10

Spearman's r_s Matrix for Working Memory Variables

	Item Memory (Error)	Item Memory (RT)	Fixed-Paced Single Errors	Fixed-Paced Single RT
Item Memory (Error)	–			
Item Memory (RT)	0.097	–		
Fixed-Paced Seated 2-Back Errors	0.422*	−0.071	–	
Fixed-Paced Seated 2-Back RT	0.136	0.324	0.009	–

Note. * $p < .05$.

Table 11

Single and Dual-Task Gait Data

		PD		Control	
		M (*SD*)	COV	*M* (*SD*)	COV
Single Walking	Velocity (cm/s)	101 (21.1)	5.00	120 (20.1)	4.70
	Stride Length (cm)	115 (15.8)	3.42	125 (13.3)	2.73
	Cycle Time (s)	1.16 (0.121)	2.71	1.05 (0.114)	2.58
	Double Support (% GC)	27.3 (6.00)	15.20	25.0 (4.78)	15.80
Fixed-Paced Dual-Task Walking	Velocity (cm/s)	89.6 (22.7)	5.88	110 (20.8)	4.25
	Stride Length (cm)	107 (17.6)	3.50	118 (13.6)	2.49
	Cycle Time (s)	1.24 (0.208)	4.92	1.09 (0.122)	2.62
	Double Support (% GC)	29.6 (6.32)	12.30	27.2 (5.96)	16.30
Self-Paced Dual-Task Walking	Velocity (cm/s)	87.7 (21.6)	4.08	108 (23.5)	3.78
	Stride Length (cm)	106 (17.1)	2.72	116 (14.0)	2.10
	Cycle Time (s)	1.25 (0.202)	2.52	1.10 (0.149)	2.51
	Double Support (% GC)	30.4 (6.38)	12.90	27.4 (5.60)	14.20

Note. COV = coefficient of variation. GC = gait cycle.

Table 12

Fixed Effect Omnibus Tests for Gait Data

			F	*df*	*p*
Gait Performance	Velocity	Group	6.81	1, 28	.014
		Walk Condition	44.47	2, 27	< .001
		Group*Walk Condition	0.83	2, 27	.445
	Stride Length	Group	3.59	1, 28	.068
		Walk Condition	56.34	2, 27	< .001
		Group*Walk Condition	1.13	2, 27	.336
	Cycle Time	Group	6.39	1, 28	.017
		Walk Condition	8.83	2, 27	.001
		Group*Walk Condition	1.47	2, 27	.248
	Double Support	Group	2.93	1, 28	.098
		Walk Condition	27.71	2, 27	< .001
		Group*Walk Condition	2.31	2, 27	.112
Gait Variability (COV)	Velocity	Group	1.89	1, 28	.180
		Walk Condition	3.67	2, 27	.032
		Group*Walk Condition	1.51	2, 27	.229
	Stride Length	Group	3.94	1, 28	.057
		Walk Condition	6.92	2, 27	.002
		Group*Walk Condition	0.57	2, 27	.571
	Cycle Time	Group	3.05	1, 28	.092
		Walk Condition	4.64	2, 27	.014
		Group*Walk Condition	4.06	2, 27	.023
	Double Support	Group	1.20	1, 28	.283
		Walk Condition	0.76	2, 27	.472
		Group*Walk Condition	0.64	2, 27	.531

Table 13

Parameter Estimates for Spatiotemporal Gait Performance

				95% CI				*SD*
	Effect	*b*	*SE b*	Lower	Upper	*t*	*p*	(random)
Velocity $R^2m = 0.223$ $R^2c = 0.966$	Intercept	102.07	4.01	94.22	109.92	25.49	< .001	21.92
	Group[a]	−20.90	8.01	−36.60	−5.20	−2.61	.014	—
	Walk 1[b]	12.88	1.36	10.22	15.55	9.47	< .001	7.25
	Walk 2[c]	2.76	0.68	1.44	4.09	4.08	< .001	3.12
	Group*Walk 1	3.51	2.72	−1.83	8.84	1.29	.208	—
	Group*Walk 2	0.81	1.35	−1.84	3.47	0.60	.554	—
Stride Length $R^2m = 0.161$ $R^2c = 0.965$	Intercept	114.14	2.86	108.53	119.74	39.89	< .001	15.66
	Group	−10.85	5.72	−22.07	0.37	−1.90	.068	—
	Walk 1	9.47	0.90	7.71	11.22	10.56	< .001	4.76
	Walk 2	1.36	0.48	0.42	2.29	2.83	.009	2.23
	Group*Walk 1	2.70	1.79	−0.82	6.21	1.50	.144	—
	Group*Walk 2	0.45	0.96	−1.43	2.33	0.47	.640	—
Cycle Time $R^2m = 0.188$ $R^2c = 0.951$	Intercept	1.156	0.029	1.099	1.214	39.234	< .001	0.160
	Group	0.149	0.059	0.034	0.265	2.529	0.017	—
	Walk 1	−0.073	0.019	−0.111	−0.035	−3.751	< 0.001	0.110
	Walk 2	−0.025	0.007	−0.038	−0.012	−3.774	< .001	0.031
	Group*Walk 1	−0.063	0.039	−0.139	0.013	−1.616	0.117	—
	Group*Walk 2	−0.007	0.013	−0.033	0.019	−0.520	0.607	—
Double Support $R^2m = 0.097$ $R^2c = 0.604$	Intercept	28.01	0.84	26.36	29.66	33.29	< .001	4.56
	Group	2.88	1.68	−0.42	6.18	1.71	.098	—
	Walk 1	−2.88	0.41	−3.68	−2.08	−7.05	< .001	1.69
	Walk 2	−0.69	0.33	−1.34	−0.04	−2.08	.040	0.62
	Group*Walk 1	−1.14	0.82	−2.74	0.46	−1.39	.174	—
	Group*Walk 2	−1.04	0.66	−2.35	0.26	−1.57	.119	—

Note. SE = standard error. $R^2m = R^2$ marginal. $R^2c = R^2$ conditional. *SD* (random) refers to the standard deviation of the random effects in the model ('—' indicates fixed effects).

[a]Group = PD – control

[b]Walk 1 = single walking – dual-task walking (fixed- and self-paced combined)

[c]Walk 2 = fixed-paced dual-task walking – self-paced dual-task walking

Table 14

Parameter Estimates for Gait Variability (COV)

				95% CI				
	Effect	*b*	*SE b*	Lower	Upper	*t*	*p*	*SD* (random)
Velocity $R^2m = 0.104$ $R^2c = 0.367$	Intercept	4.62	0.27	4.08	5.15	16.99	< .001	1.11
	Group	0.75	0.54	−0.32	1.81	1.37	.180	—
	Walk 1	0.35	0.38	−0.41	1.10	0.91	.368	—
	Walk 2	1.13	0.44	0.26	2.00	2.56	.013	—
	Group*Walk 1	−0.67	0.77	−2.18	0.84	−0.87	.388	—
	Group*Walk 2	1.34	0.89	−0.40	3.08	1.51	.137	—
Stride Length $R^2m = 0.140$ $R^2c = 0.675$	Intercept	2.83	0.19	2.45	3.21	14.56	< .001	0.97
	Group	0.77	0.39	0.01	1.53	1.99	.057	—
	Walk 1	0.37	0.17	0.04	0.70	2.19	.033	—
	Walk 2	0.59	0.20	0.21	0.97	3.01	.004	—
	Group*Walk 1	−0.11	0.34	−0.78	0.55	−0.34	.737	—
	Group*Walk 2	0.39	0.39	−0.37	1.16	1.01	.318	—
Cycle Time $R^2m = 0.173$ $R^2c = 0.307$	Intercept	2.98	0.23	2.52	3.43	12.81	< .001	0.77
	Group	0.81	0.47	−0.10	1.72	1.75	.092	—
	Walk 1	−0.50	0.39	−1.27	0.27	−1.28	.206	—
	Walk 2	1.25	0.45	0.36	2.14	2.77	.008	—
	Group*Walk 1	−1.02	0.79	−2.56	0.51	−1.30	.197	—
	Group*Walk 2	2.29	0.91	0.52	4.07	2.53	.014	—
Double Support $R^2m = 0.042$ $R^2c = 0.258$	Intercept	14.46	0.89	12.72	16.20	16.28	< .001	3.32
	Group	−1.95	1.78	−5.43	1.54	−1.10	.283	—
	Walk 1	1.58	1.38	−1.12	4.27	1.14	.257	—
	Walk 2	0.73	1.59	−2.38	3.85	0.46	.646	—
	Group*Walk 1	2.12	2.75	−3.28	7.51	0.77	.446	—
	Group*Walk 2	−2.65	3.18	−8.88	3.59	−0.83	.409	—

Note. SE = standard error. $R^2m = R^2$ marginal. $R^2c = R^2$ conditional. *SD* (random) refers to the standard deviation of the random effects in the model ('—' indicates fixed effects).

[a]Group = PD – control

[b]Walk 1 = single walking – dual-task walking (fixed- and self-paced combined)

[c]Walk 2 = fixed-paced dual-task walking – self-paced dual-task walking

Table 15

Descriptives for Dual-Task Effects (%) to Cognitive and Gait Variables

		M (*SD*)	
		PD	Control
Cognitive	*N*-Back RT (Fixed)	−3.74 (15.09)	−2.06 (19.05)
	N-Back RT (Self)	1.38 (14.48)	5.24 (15.91)
	N-Back Accuracy (Fixed)	−10.00 (5.33)	−10.71 (9.35)
	N-Back Accuracy (Self)	−4.87 (9.94)	−4.58 (5.93)
Gait Performance	Velocity (Fixed)	−14.10 (9.47)	−8.42 (6.33)
	Velocity (Self)	−17.37 (11.21)	−10.78 (7.44)
	Stride Length (Fixed)	−9.12 (5.23)	−6.09 (3.45)
	Stride Length (Self)	−10.58 (6.67)	−7.01 (3.94)
	Cycle Time (Fixed)	−7.26 (9.44)	−2.93 (4.20)
	Cycle Time (Self)	−9.67 (11.52)	−4.74 (5.08)
	Double Support (Fixed)	−10.42 (6.58)	−9.10 (11.24)
	Double Support (Self)	−14.89 (6.63)	−9.47 (7.70)
Gait Variability (COV)	Velocity (Fixed)	−30.89 (72.09)	2.30 (47.29)
	Velocity (Self)	12.00 (36.35)	14.73 (47.98)
	Stride Length (Fixed)	−14.95 (50.30)	5.15 (35.65)
	Stride Length (Self)	12.48 (35.46)	21.26 (26.93)
	Cycle Time (Fixed)	−116.03 (182.32)	−8.01 (46.04)
	Cycle Time (Self)	−25.31 (99.69)	−1.30 (56.17)
	Double Support (Fixed)	−0.28 (72.07)	−52.60 (107.66)
	Double Support (Self)	−7.87 (89.97)	−26.84 (102.70)

Note. Dual-task effects were calculated as (dual performance – single performance) / single performance * 100%

Table 16

Results of the Dual-Task Effect Analyses

			F	*p*	η^2
Cognitive Performance	Reaction Time	Group	0.27	.606	.007
		Pacing	5.57	.026	.037
		Group*Pacing	0.17	.681	.001
	Accuracy	Group	0.01	.919	< .001
		Pacing	7.76	.009	.119
		Group*Pacing	0.06	.807	< .001
Gait Performance	Velocity	Group	3.81	.061	.112
		Pacing	16.42	< .001	.024
		Group*Pacing	0.43	.517	.001
	Stride Length	Group	3.50	.072	.104
		Pacing	7.16	.012	.014
		Group*Pacing	0.36	.553	.001
	Cycle Time	Group	2.51	.125	.078
		Pacing	15.62	< .001	.016
		Group*Pacing	0.31	.580	< .001
	Double Support	Group	1.37	.251	.041
		Pacing	7.00	.013	.021
		Group*Pacing	5.03	.033	.015
Gait Variability (COV)	Velocity	Group	1.25	.273	.028
		Pacing	6.91	.014	.066
		Group*Pacing	2.09	.159	.020
	Stride Length	Group	1.35	.255	.034
		Pacing	12.25	.002	.078
		Group*Pacing	0.83	.371	.005
	Cycle Time	Group	4.13	.052	.081
		Pacing	4.23	.049	.044
		Group*Pacing	3.15	.087	.033
	Double Support	Group	1.24	.275	.037
		Pacing	0.53	.473	.002
		Group*Pacing	1.78	.193	.008

Note. Each *F* had degrees of freedom of 1, 28.

Table 17

Spearman's r_s Matrix for Cognitive Domains and Walking Variables

	Single Velocity	DTE Velocity	COV Single Velocity	COV DTE Velocity	Vigilance	Executive Control	Working Memory
Single Velocity	—						
DTE Velocity	.400*	—					
COV Single Velocity	−.537**	−.385*	—				
COV DTE Velocity	−.080	.241	.501**	—			
Vigilance	.203	.385*	−.470**	−.010	—		
Executive Control	.366*	.285	−.419*	−.150	.547**	—	
Working Memory	.080	.185	−.190	.036	.639***	.561**	—

Note. * $p < .05$. ** $p < .01$. *** $p < .001$.

Table 18

Predictors for Single Velocity

			95% CI				
	b	*SE b*	Lower	Upper	*β*	*t*	*p*
Model 1							
Intercept	119.94	5.27	109.16	130.73	—	22.78	< .001
Group (PD − Control)	−18.54	7.45	–33.80	–3.28	−0.43	−2.49	.019
Model 2							
Intercept	116.59	5.21	105.91	127.28	—	22.39	< .001
Group (PD − Control)	−11.84	7.69	−27.63	3.95	−0.27	−1.54	.135
Executive Control	16.00	7.53	0.56	31.45	0.38	2.13	.043

Note. I used SPSS instead of jamovi for this analysis, because jamovi uses grand mean centering when computing the intercept for linear regression models (see link). The only difference between the outputs from SPSS and jamovi here relates to the intercepts.

$R^2_{\text{Model 1}} = .181$, $p = .019$, $\Delta R^2_{\text{Model 2}} = .117$, $p = .043$.
VIF = 1.202
Tolerance = 0.832
Model 1 overall was significant, $F(1, 28) = 6.197$, $p = .019$
Model 2 overall was significant, $F(2, 27) = 5.750$, $p = .008$

Table 19

Predictors for DTE Velocity

			95% CI				
	b	*SE b*	Lower	Upper	*β*	*t*	*p*
Model 1							
Intercept	−8.42	2.08	−12.68	−4.16	—	−4.05	< .001
Group (PD − Control)	−5.68	2.94	−11.70	0.35	−0.34	−1.93	.064
Model 2							
Intercept	−9.37	2.05	−13.58	−5.17	—	−4.57	< .001
Group (PD − Control)	−3.78	2.98	−9.90	2.35	−0.23	−1.27	.217
Vigilance	4.01	2.11	−0.31	8.34	0.34	1.90	.068

Note. I used SPSS instead of jamovi for this analysis, because jamovi uses grand mean centering when computing the intercept for linear regression models (see link). The only difference between the outputs from SPSS and jamovi here relates to the intercepts.

$R^2_{\text{Model 1}} = .118$, $p = .064$, $\Delta R^2_{\text{Model 2}} = .104$, $p = .068$
VIF = 1.126
Tolerance = 0.888
Model 1 overall was not significant, $F(1, 28) = 3.730$, $p = .064$
Model 2 overall was significant, $F(2, 27) = 3.851$, $p = .034$

Table 20

Predictors for Single Velocity Variability (COV)

			95% CI				
	b	*SE b*	Lower	Upper	*β*	*t*	*p*
Model 1							
Intercept	4.70	0.48	3.72	5.67	—	9.88	< .001
Group (PD − Control)	0.30	0.67	−1.08	1.68	0.08	0.45	.658
Model 2							
Intercept	5.04	0.45	4.11	5.96	—	11.21	< .001
Group (PD − Control)	−0.38	0.67	−1.75	0.99	−0.11	−0.57	.574
Vigilance	−1.21	0.60	−2.44	0.03	−0.48	−2.01	.055
Executive Control	−0.26	0.86	−2.02	1.51	−0.07	−0.30	.768

Note. I used SPSS instead of jamovi for this analysis, because jamovi uses grand mean centering when computing the intercept for linear regression models (see link). The only difference between the outputs from SPSS and jamovi here relates to the intercepts.

$R^2_{\text{Model 1}} = .007$, $p = .658$, $\Delta R^2_{\text{Model 2}} = .247$, $p = .024$
VIF (vigilance, executive control) = 1.126, 1.201
Tolerance (vigilance, executive) = .888, .832
Model 1 overall was not significant, $F(1, 28) = .200$, $p = .658$
Model 2 overall was significant, $F(2, 27) = 2.948$, $p = .051$.

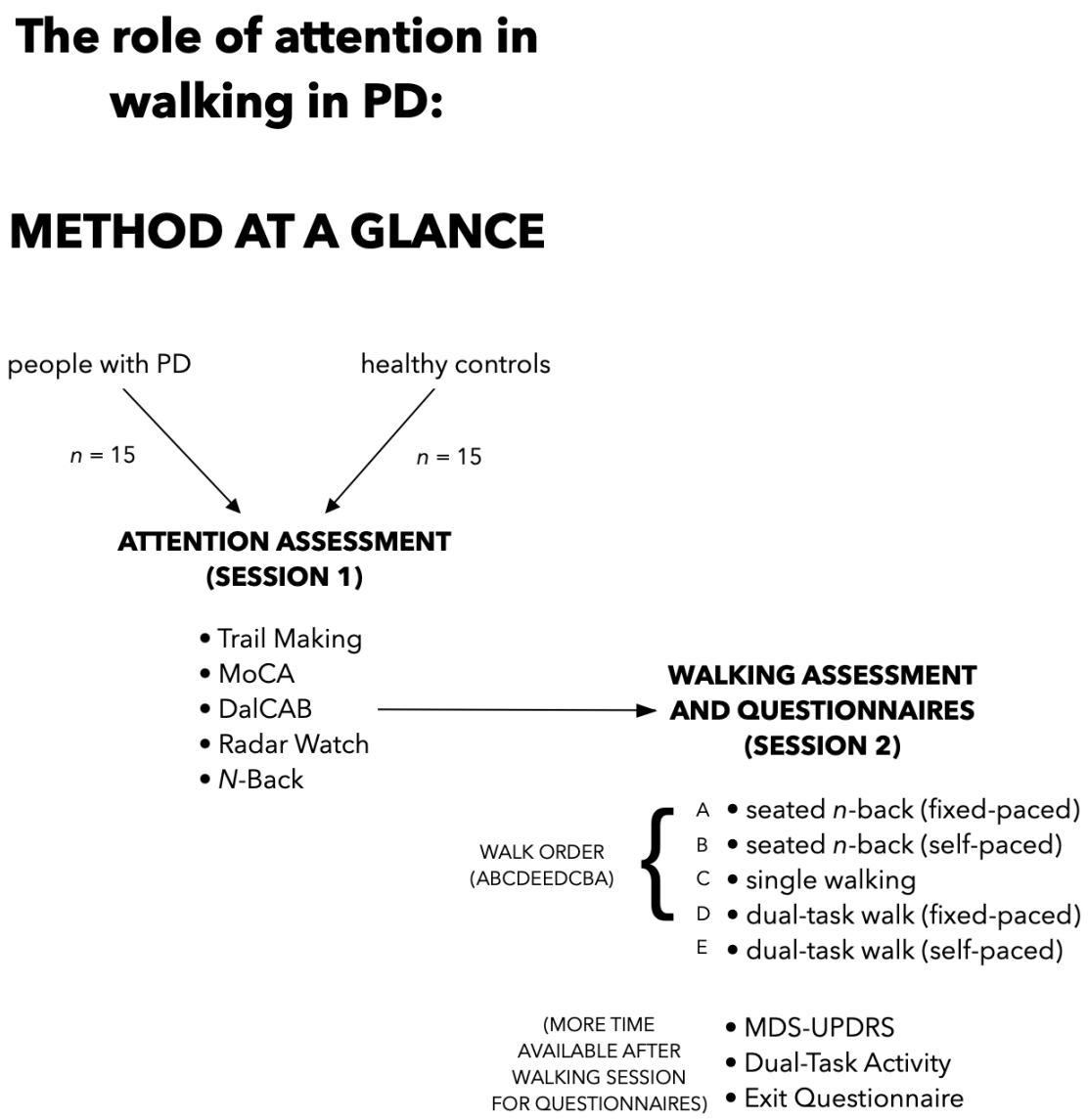

Figure 1. Flow chart showing the study procedure. The *n*-back program used is an auditory *n*-back with letter stimuli. Session 1 *n*-back data were not used; we were interested in dual-task effects and not differences attributable to learning the task. During session 1, participants played two blocks of fixed-paced *n*-back at $n = 1$, followed by two blocks of $n = 2$, and finally two blocks of self-paced *n*-back at $n = 2$.

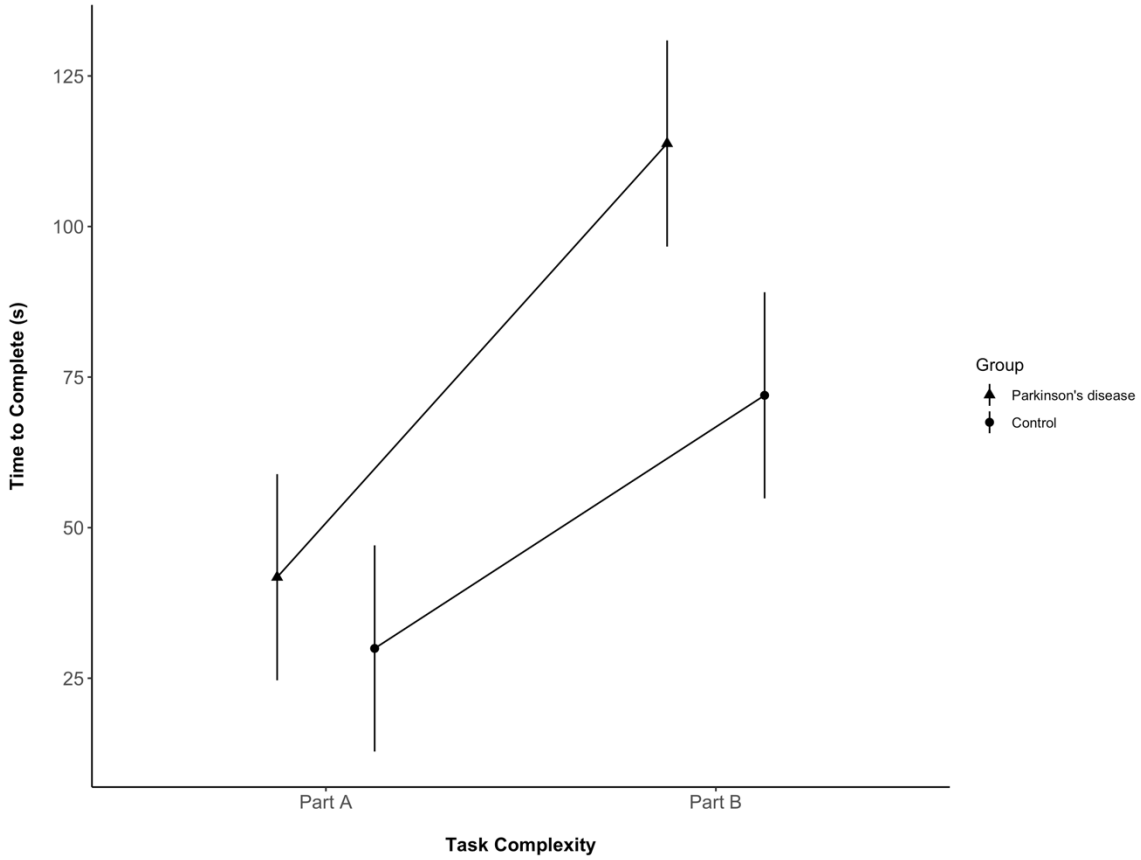

Figure 2. Results of the 2 x 2 ANOVA for the Trail Making Test, examining the effects of group and task complexity on time to completion. Both main effects were significant, but the interaction was not. Error bars represent 95% confidence intervals.

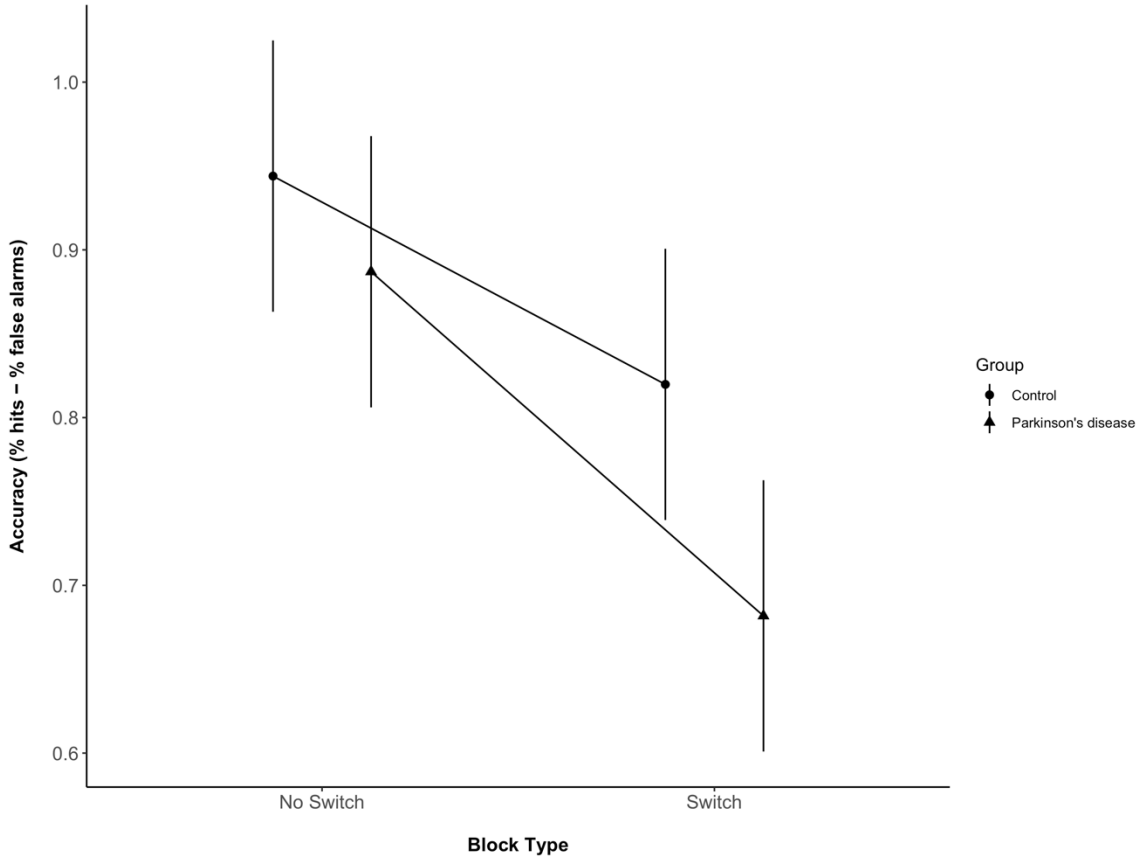

Figure 3. Results of the 2 x 2 ANOVA for Radar Watch, comparing the effects of group and block type on accuracy. Main effects were significant, but there were no interactions. Error bars represent 95% confidence intervals.

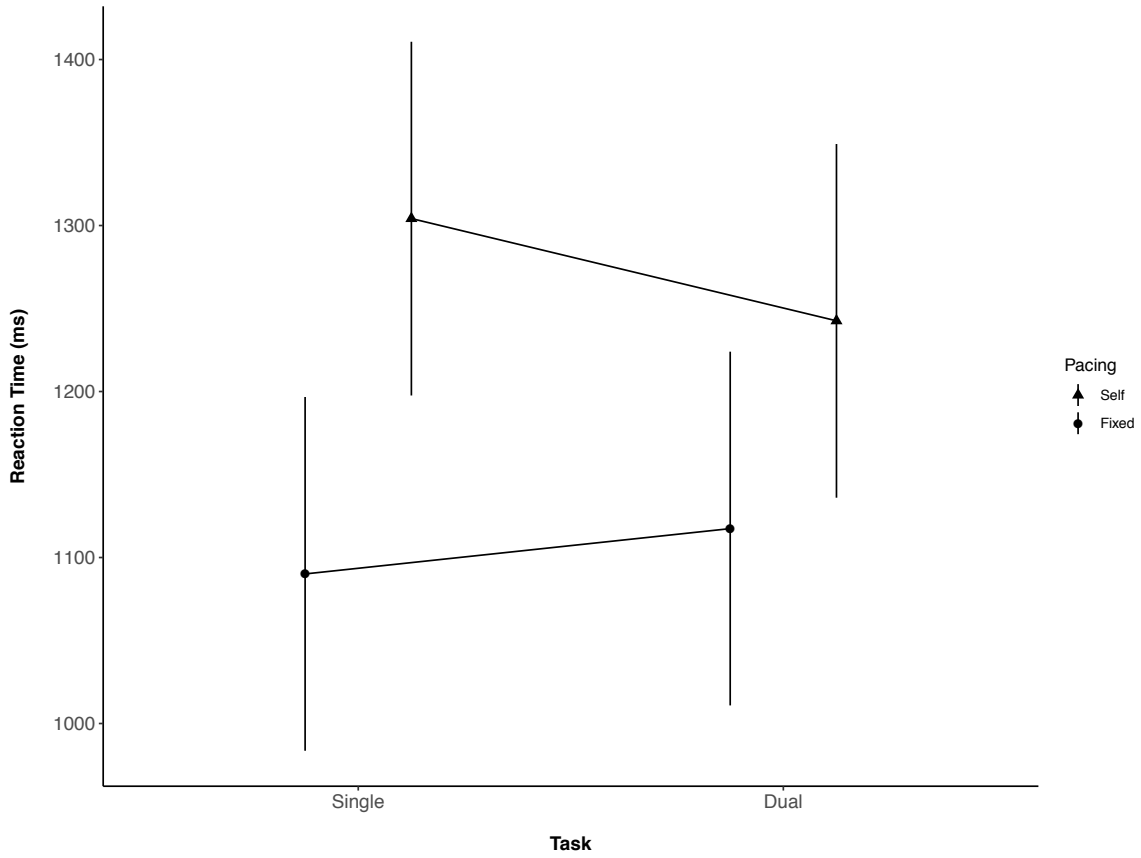

Figure 4. Results of the 2 x 2 x 2 ANOVA for *n*-back RT, comparing the effects of pacing, task, and group. Group is not shown in this graph because RTs did not significantly differ between groups. There was a significant main effect of pacing and interaction between task and pacing.

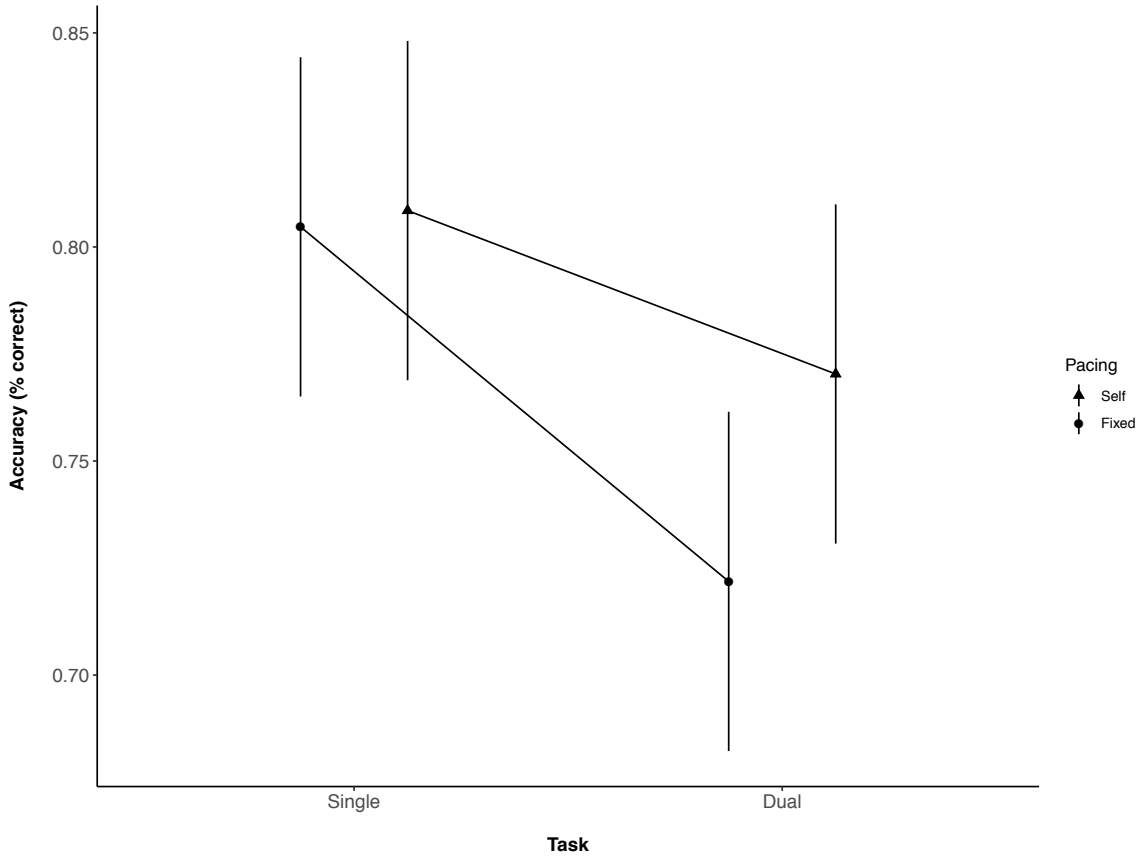

Figure 5. Results of the 2 x 2 x 2 ANOVA for *n*-back accuracy, comparing the effects of pacing, task, and group. Group is not shown in this graph because accuracy did not significantly differ between groups. There were significant main effects of task and pacing, and an interaction of task by pacing.

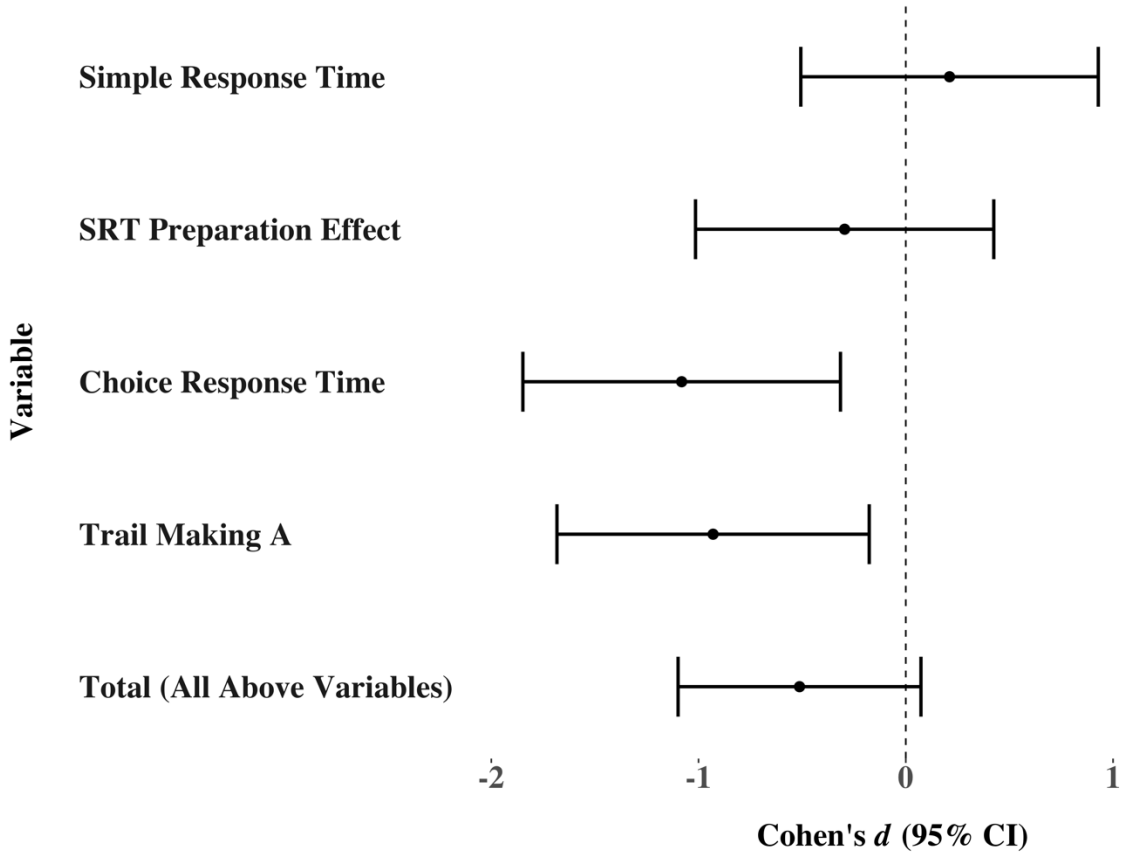

Figure 6. Cohen's *d* forest plots for vigilance. Scores to the left of the dashed line (0) indicate worse performance in the PD group compared to the control group (i.e., longer RTs and a larger number of errors). Error bars represent 95% confidence intervals; variables are significantly differed between groups when error bars do not cross the dashed line. The *x*-axis, Cohen's *d*, is interpretable as number of standard deviations separating the PD and control groups.

Note. SRT = simple response time.

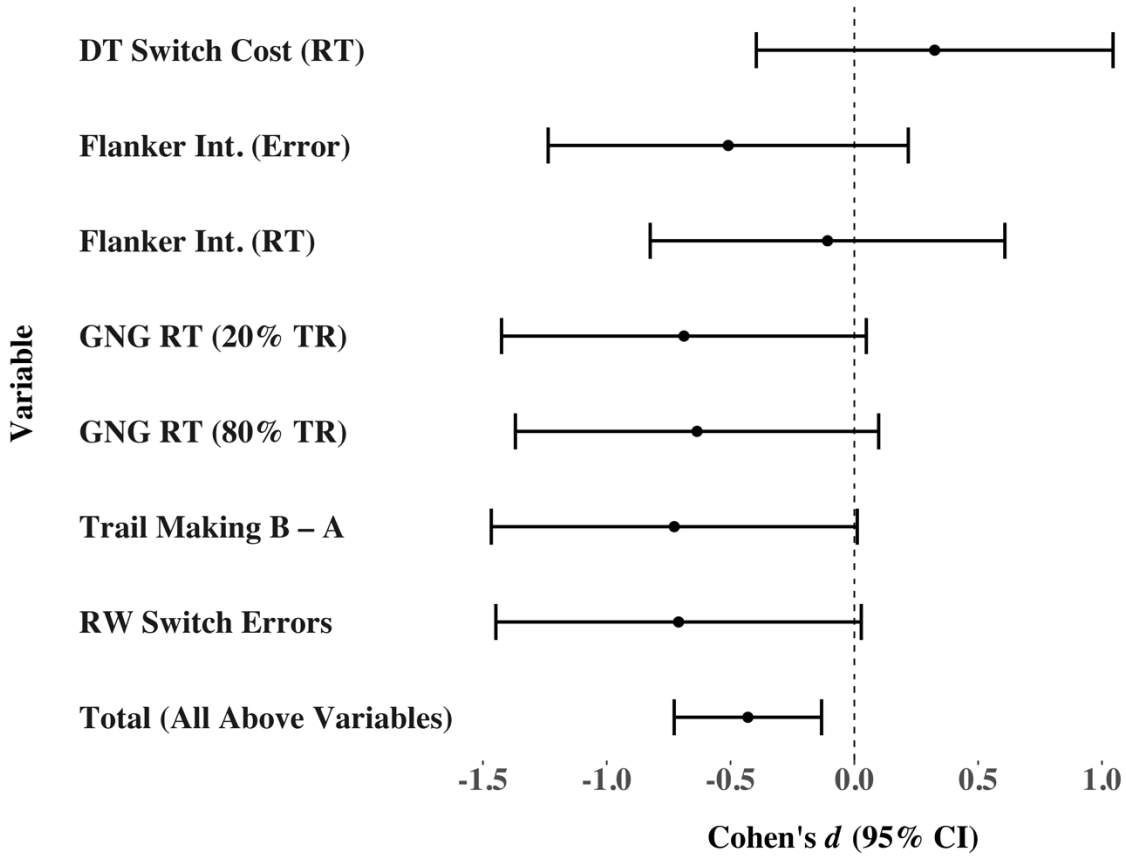

Figure 7. Cohen's *d* forest plots for executive control. Scores to the left of the dashed line (0) indicate worse performance in the PD group compared to the control group. Error bars represent 95% confidence intervals; variables are significantly differed between groups when error bars do not cross the dashed line. The *x*-axis, Cohen's *d*, is interpretable as number of standard deviations separating the PD and control groups.

Note. DT = dual task. Flanker Int. = Flanker interference. GNG = go/no-go. RT = reaction time. TR = target rate.

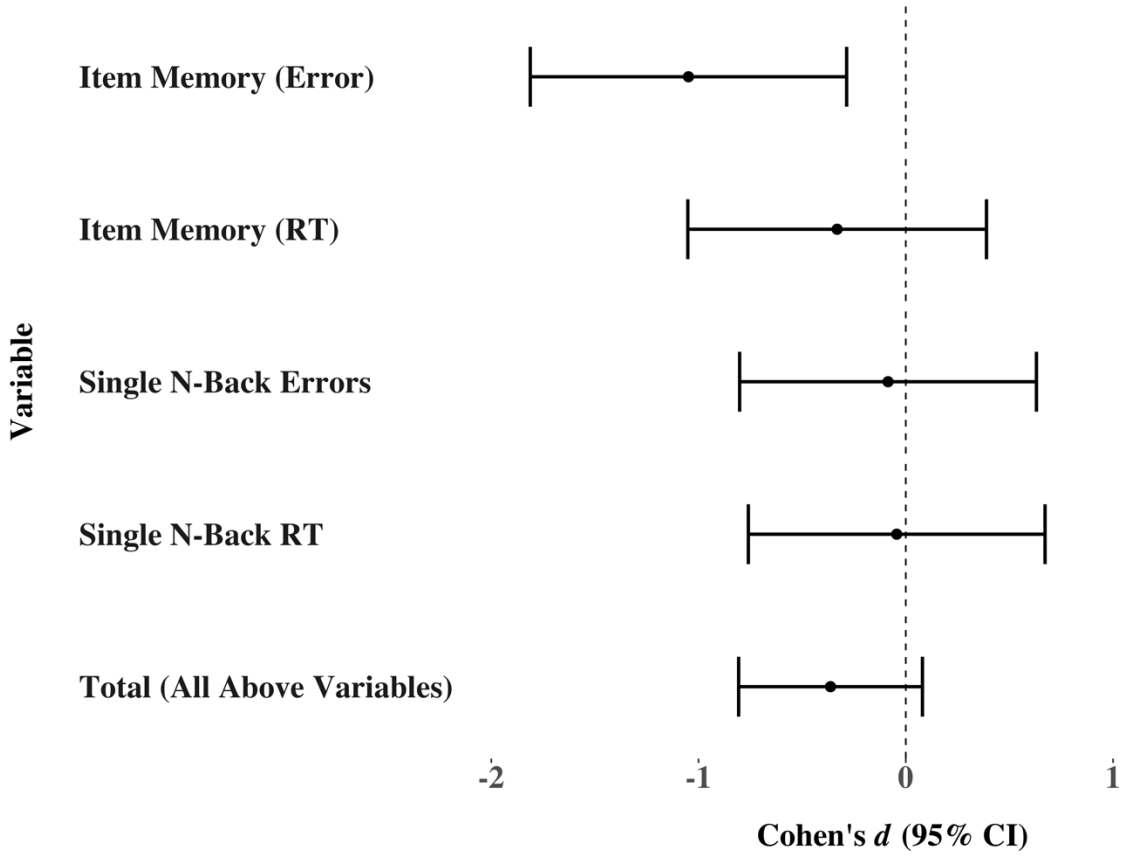

Figure 8. Cohen's *d* forest plots for working memory. Scores to the left of the dashed line (0) indicate worse performance in the PD group compared to the control group. Error bars represent 95% confidence intervals; variables are significantly differed between groups when error bars do not cross the dashed line. The *x*-axis, Cohen's *d*, is interpretable as number of standard deviations separating the PD and control groups.

Note. RT = reaction time.

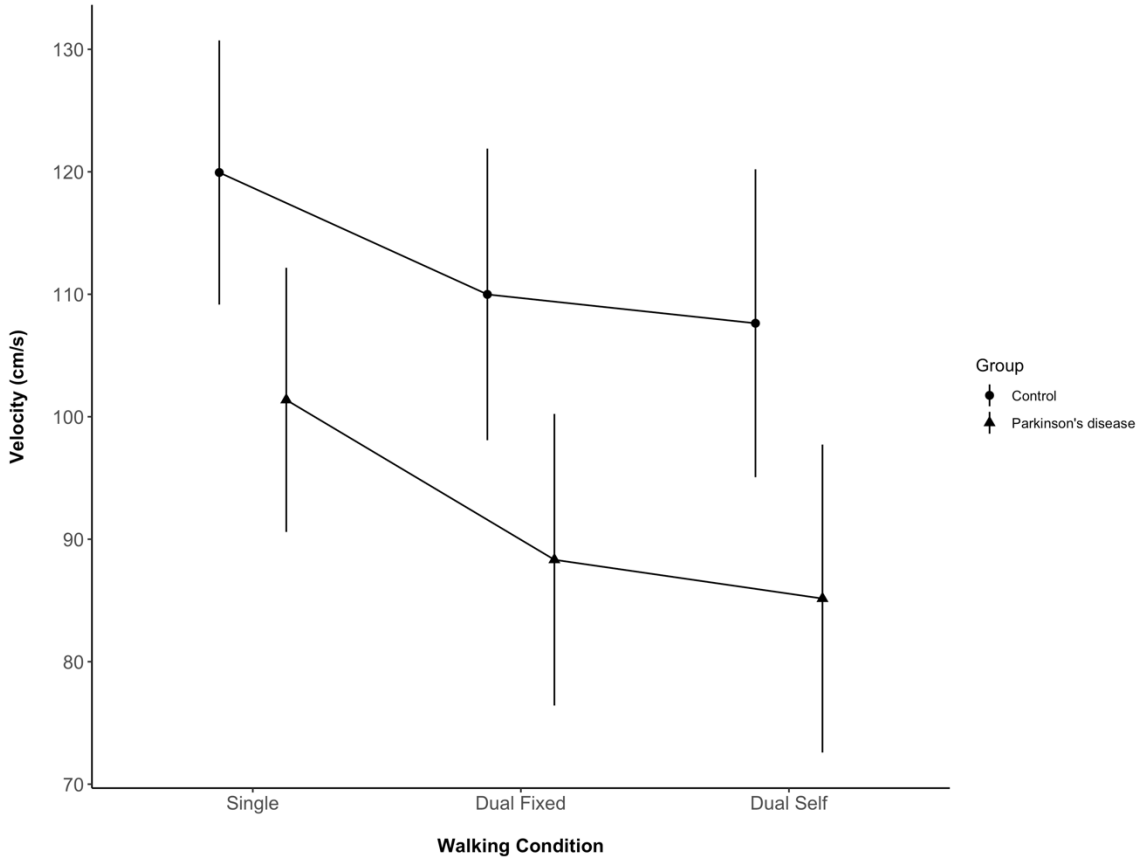

Figure 9. Estimated marginal means for condition and group plotted from the linear mixed model for velocity. Error bars represent 95% confidence intervals. The groups show a remarkably similar pattern of results between walking conditions, though people with PD walk consistently slower.

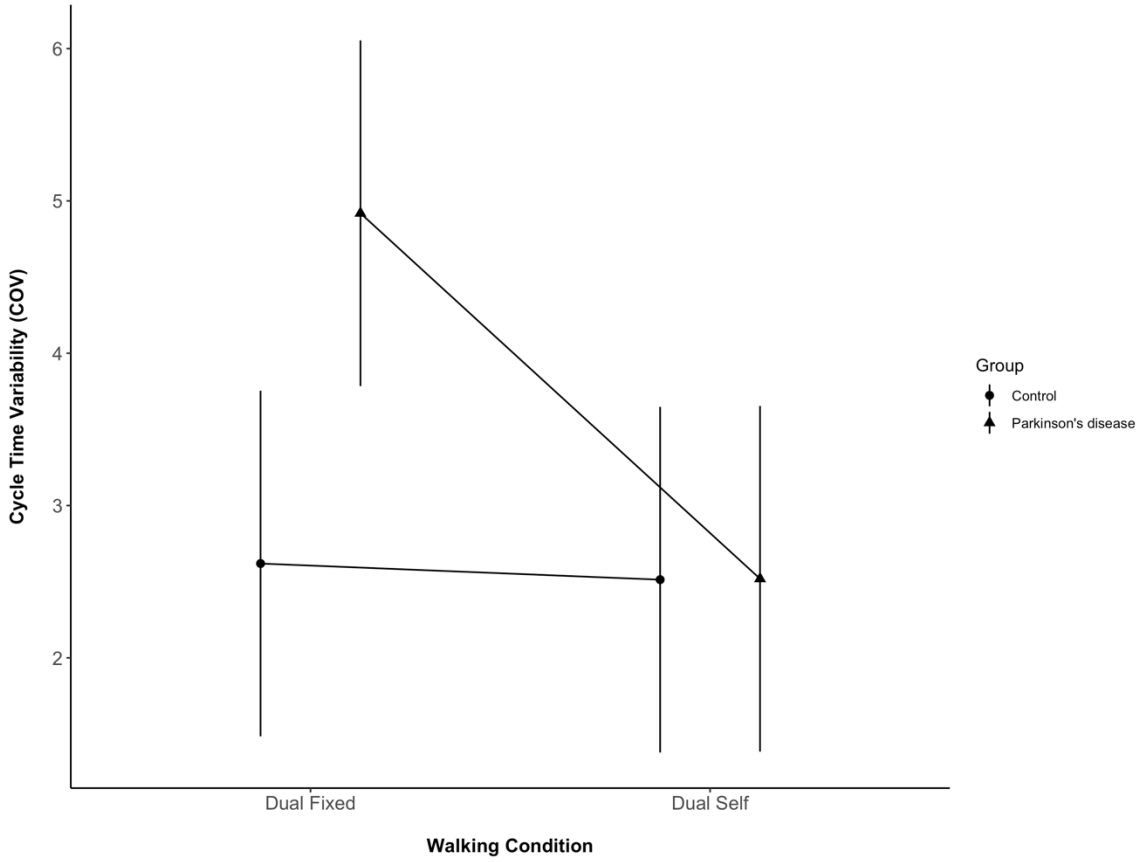

Figure 10. Estimated marginal means showing the interaction between group and dual-task pacing for cycle time variability (as measured by COV).

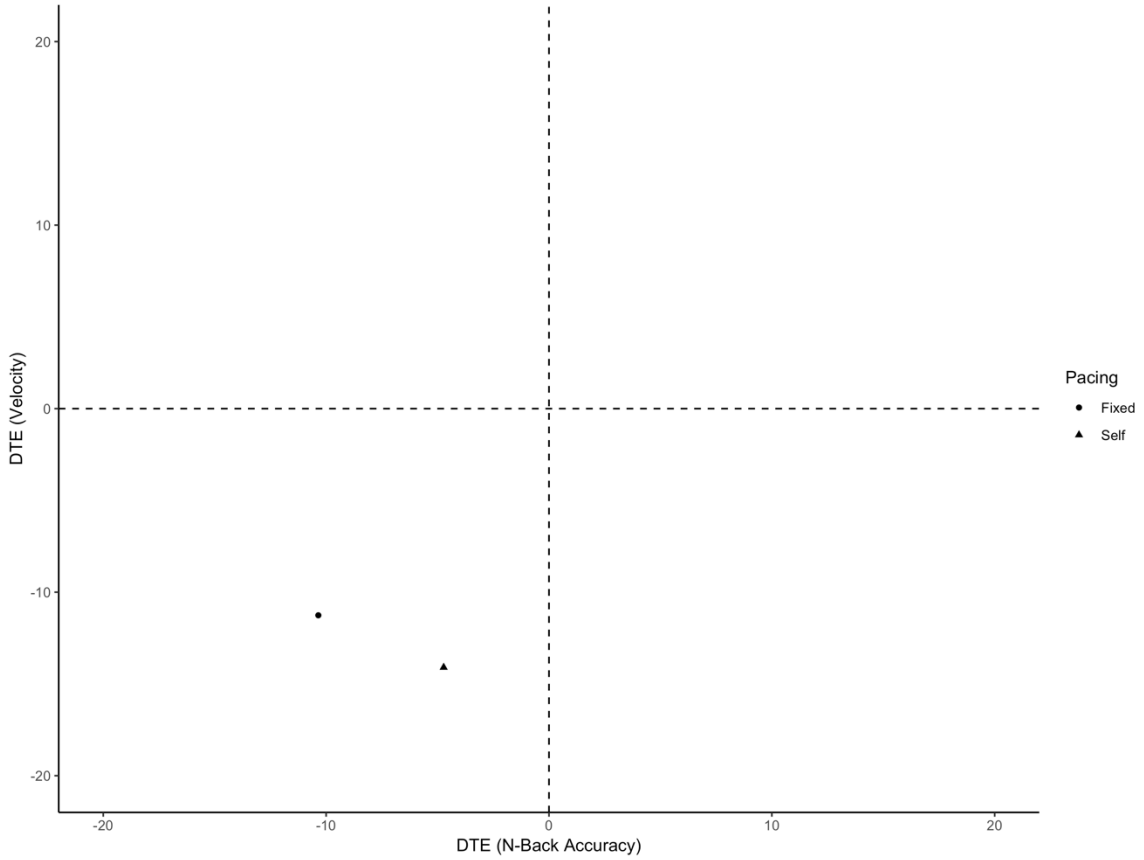

Figure 11. Dual-task effect plot for velocity and *n*-back accuracy. Points are in the lower-left quadrant, meaning that dual-task performance was worse than single-task performance in all cases.

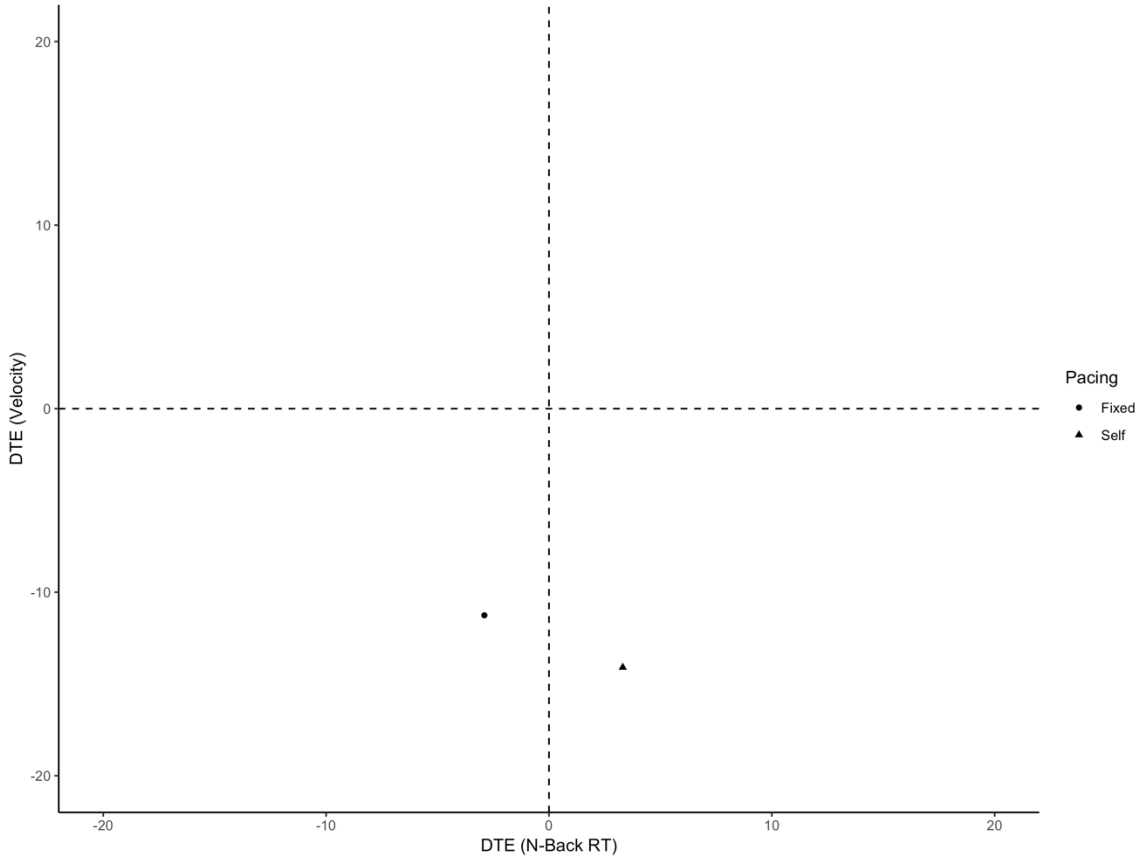

Figure 12. Dual-task effect plot for velocity and *n*-back RT. The fixed-paced point is in the lower-left quadrant, meaning that dual-task performance was worse than single-task performance. The self-paced scores, however, show a relative increase in RT during dual trials, suggesting that walking affected the tempo of their responses.

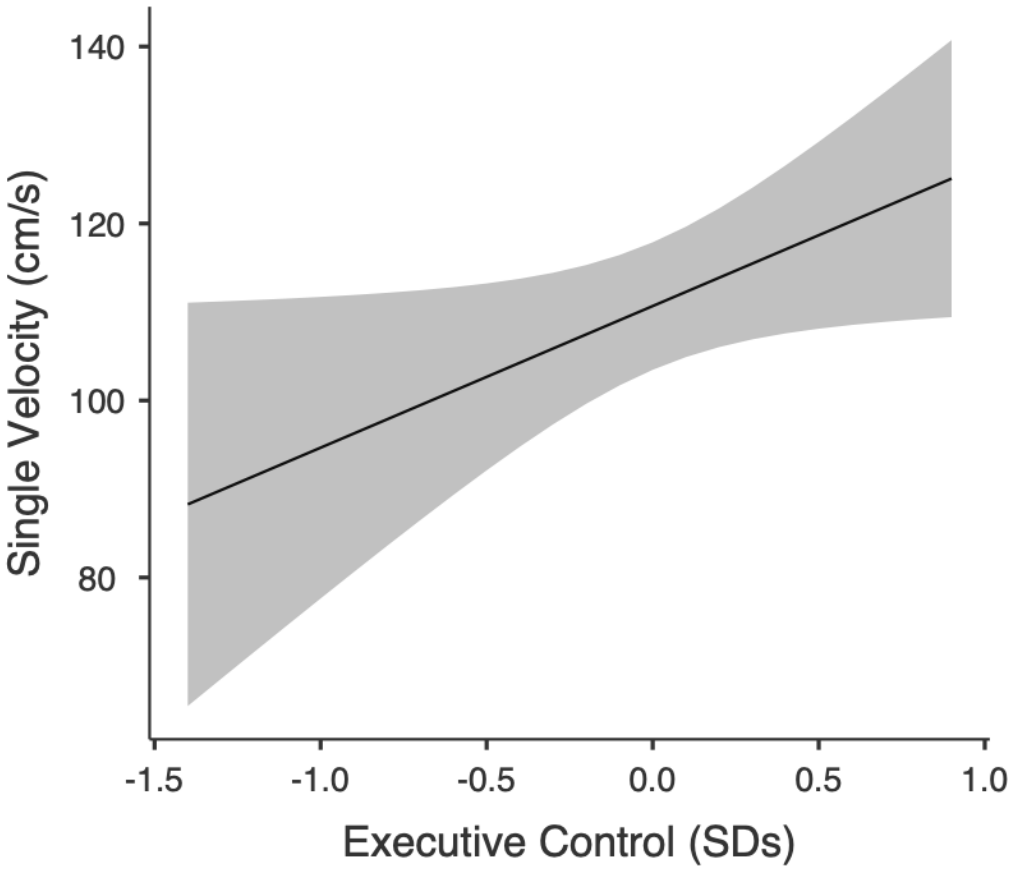

Figure 13. Single velocity as a function of executive control performance. Executive control significantly predicted 11.7% of the variance in single walking speed in this study. This graph shows how velocity changes as a function of executive control, independent of group, expressed in standard deviations above or below the mean. The shaded region on the figure represents a 95% confidence interval band.

Appendix A: Screening Form

(Ethical Approval: NSHA ROMEO File # 1024105)

Participant ID: _____ Group: _____ Date: _____

Background and Health History

Demographics:

Email or Phone (if consent):

Handedness:

Education (years):

Gender:

Occupation (or previous occupation if retired):

Date of Birth (month and year only):

Age:

First Language:

Health Information:

What is your general state of health? Excellent very good good fair poor

Have you ever been diagnosed or treated for any of the following: If YES: Details (meds and time since diagnosis)

- Head injury with loss of consciousness? YES NO
- Seizures? YES NO
- Multiple Sclerosis? YES NO
- Parkinson's Disease? YES NO
- Huntington's Disease? YES NO
- Stroke? YES NO
- Dominant upper limb pain, arthritis, or injury? YES NO
- Sleep Apnea? YES NO
- Heart Attack? YES NO
- Surgery with general anesthetic in the past 6 months? YES NO
- Visual Problems? YES NO
  - Glasses? If yes, are they present? YES NO
  - Colour blindness? YES NO
- Trouble Hearing? YES NO

- Hearing aid? If yes, is it present? YES NO

Are there any other health issues that we haven't asked about?

Participant ID: _____ Date: _____

Medications:

Computer Experience:

Experience using a computer	1 = **No Experience**	2 = **Rarely** (i.e. once a year)	3 = **Sometimes** (i.e. once a month)	4 = **Often** (i.e. once a week)	5 = **Regularly** (i.e. once a day)

Within the last six months, how many hours per week do you use a computer?

_____ What are the 3 computer programs you use most often?

1._____

2._____

3._____

Gaming Experience:

Within the last six months, how many hours per week do you play digital games (e.g. games on a computer, phone, tablet, or video game console)?

_____ What are the 3 digital games you play most often?

1._____

2._____

3._____

Walking/Physical Activity:

Within the last six months, how many hours per day do you spend doing physical activity (e.g., walking, gardening, biking, etc.)?

Is walking ever difficult? If so, when do you find walking difficult?

Do you use any mental or physical **strategies to help you walk better?**

Do you tend to focus on walking, or are you usually thinking about other things?

Have you been in a situation in which you fell or almost fell? What were you doing?

Do you avoid any activities because you are afraid of falling?

If PD: Are there any activities you are no longer able to do because of your Parkinson's?

Health Changes (Session 2 only):

Have there been any changes to your health since your first session?

Appendix B: Exit Questionnaire

1. While doing the auditory n-back task (the one where you kept track of letters and clicked to indicate whether a letter was a target), did you use any special strategies to help keep track of the matches?

2. How did you find combining this task with walking? Did you use any strategy, either for walking or for the auditory n-back, to help you do both better?

3. Did you put equal effort into walking and the task, or did you prioritize one?

4. While doing the DalCAB activities (the activities with the playing cards), did you use any particular strategy? What was going through your mind while you were completing these tasks?

5. Do you have any comments about the study?

Appendix C: Dual-Task Effect Plots for All Gait Variables

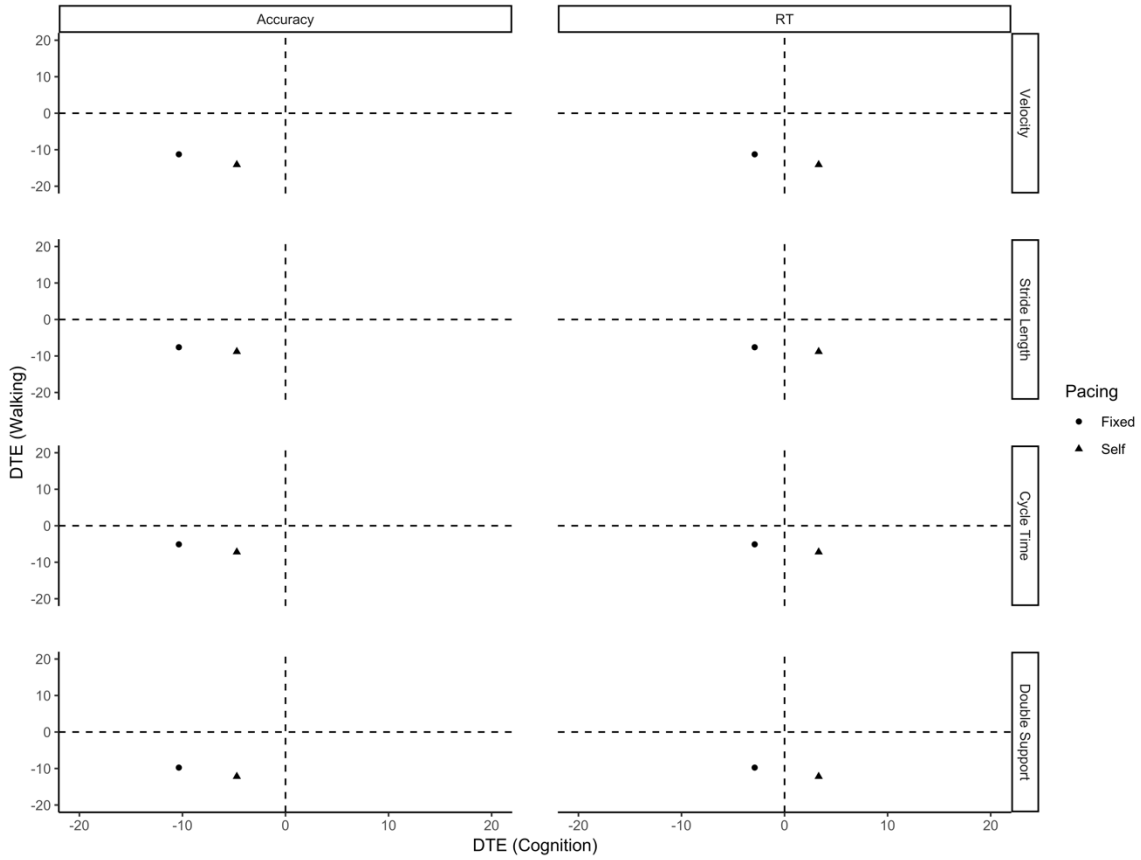

Figure 13. This facet plot shows DTE plots for both accuracy and RT, for all gait variables. We multiplied DTEs for cycle time and double support by -1 to standardize interpretation, such that scores falling in the lower left quadrant always indicated worse performance to both cognition and gait. The pattern of results is remarkably similar across the gait variables.