JSLHR

Research Article

Effects of Concurrent Manual Task Performance on Connected Speech Acoustics in Individuals With Parkinson Disease

Jason A. Whitfield,[a] Zoe Kriegel,[a] Adam M. Fullenkamp,[b] and Daryush D. Mehta[c]

Purpose: Prior investigations suggest that simultaneous performance of more than 1 motor-oriented task may exacerbate speech motor deficits in individuals with Parkinson disease (PD). The purpose of the current investigation was to examine the extent to which performing a low-demand manual task affected the connected speech in individuals with and without PD.

Method: Individuals with PD and neurologically healthy controls performed speech tasks (reading and extemporaneous speech tasks) and an oscillatory manual task (a counterclockwise circle-drawing task) in isolation (single-task condition) and concurrently (dual-task condition).

Results: Relative to speech task performance, no changes in speech acoustics were observed for either group when the low-demand motor task was performed with the concurrent reading tasks. Speakers with PD exhibited a significant decrease in pause duration between the single-task (speech only) and dual-task conditions for the extemporaneous speech task, whereas control participants did not exhibit changes in any speech production variable between the single- and dual-task conditions.

Conclusions: Overall, there were little to no changes in speech production when a low-demand oscillatory motor task was performed with concurrent reading. For the extemporaneous task, however, individuals with PD exhibited significant changes when the speech and manual tasks were performed concurrently, a pattern that was not observed for control speakers.

Supplemental Material: https://doi.org/10.23641/asha.8637008

Most activities of daily living require highly skilled, automatic control over the motor system. Although highly skilled speech movements that are well learned can be performed with little effort, data from several studies suggest skilled motor performance is affected by completion of a secondary task that demands attentional resources (e.g., Dromey & Bates, 2005; Dromey & Benson, 2003; Dromey & Shim, 2008). The concurrent, dual-task paradigm has been used to examine the effect of competing task demands on speech and nonspeech motor control (e.g., Dromey & Benson, 2003). In dual-task studies, participants perform two tasks simultaneously, for example, walking and talking. Each task is performed in isolation (i.e., under single-task conditions), and then the tasks are performed concurrently (i.e., under dual-task conditions). The term *dual-task interference* refers to poorer performance in the dual- compared to single-task condition. Dual-task interference patterns can be unidirectional, affecting only one of the simultaneously performed tasks, or bidirectional, affecting performance of both tasks (e.g., Bailey & Dromey, 2015; Dromey et al., 2010). The cost of performing two tasks simultaneously is suggested to reflect the combined attentional resources required to complete each task (Kemper, Schmalzried, Herman, Leedahl, & Mohankumar, 2009). The aim of the current investigation was

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[a] Department of Communication Sciences and Disorders, Bowling Green State University, OH
[b] School of Human Movement, Sport, & Leisure Studies, Bowling Green State University, OH
[c] Center for Laryngeal Surgery and Voice Rehabilitation, Department of Surgery, Massachusetts General Hospital–Harvard Medical School, Boston

Correspondence to Jason A. Whitfield: jawhitf@bgsu.edu

Editor-in-Chief: Michael Hammer
Editor: Cara Stepp

Received May 17, 2018
Revision received September 27, 2018
Accepted January 21, 2019
https://doi.org/10.1044/2019_JSLHR-S-MSC18-18-0190

Publisher Note: This article is part of the Forum: Selected Papers From the 2018 Conference on Motor Speech—Basic Science and Clinical Innovation.

Disclosure: *The authors have declared that no competing interests existed at the time of publication.*

to examine the extent to which a concurrent, simple motor task affected speech production in individuals with PD.

Effect of Dual-Task Conditions on Motor Control

Data suggest that dual-task performance affects basic aspects of motor control in neurologically healthy participants, especially when the secondary task requires attentional demands (e.g., Bergamin et al., 2014; Ebersbach, Dimitrijevic, & Poewe, 1995; Kemper et al., 2009). Relative to speech motor control, Dromey and colleagues have examined the effect of several secondary tasks on speech motor stability in healthy young adult participants, including motor, cognitive, linguistic, and visuomotor tasks (i.e., Bailey & Dromey, 2015; Dromey & Bates, 2005; Dromey & Benson, 2003; Dromey & Shim, 2008). These data suggest that, in healthy control participants, secondary tasks requiring attentional resources, such as language formulation, linguistic decision making, and cognitive manipulation, impact spatiotemporal parameters of lip movement stability to a greater extent than simple motor tasks (e.g., Bailey & Dromey, 2015; Dromey & Bates, 2005; Dromey & Benson, 2003). Comparison of the results from multiple studies by Dromey and colleagues may suggest that the demands of both the speech and secondary tasks mediate the degree of dual-task interference observed in healthy talkers (Bailey & Dromey, 2015; Dromey & Bates, 2005; Dromey & Benson, 2003; Dromey & Shim, 2008).

Parkinson disease (PD) is a progressive neurological disorder that affects motor control, often leading to changes in gait, posture, handwriting, and speech production (e.g., Jankovic, 2008). These deficits arise from the cardinal motor symptoms associated with PD, which include tremor, rigidity, bradykinesia, and postural instability. Approximately 70%–90% of individuals with PD will experience hypokinetic dysarthria over the course of the disease (e.g., Müller et al., 2001), which is often characterized by a reduction in vocal loudness, monopitch, monoloudness, an accelerating or festinating rate, disfluency, and articulatory imprecision (e.g., Darley, Aronson, & Brown, 1969). Studies of dual-task performance across speech, posture, and gait domains have found that individuals with PD often exhibit a worsening of speech and nonspeech motor deficits when performing more than one task at a time (e.g., Brown, de Bruin, Doan, Suchowersky, & Hu, 2009; Bunton & Keintz, 2008; Dromey et al., 2010; Foreman et al., 2013; Ho, Iansek, & Bradshaw, 2002; Holmes, Jenkins, Johnson, Adams, & Spaulding, 2010; LaPointe, Stierwalt, & Maitland, 2010; McCaig, Adams, Dykstra, & Jog, 2016; O'Shea, Morris, & Iansek, 2002; Whitfield & Goberman, 2017b). However, relatively few investigations have reported on the effect of a concurrently performed simple manual task on speech (e.g., Bunton & Keintz, 2008) and gait (e.g., O'Shea et al., 2002) in individuals with PD.

Dual-task investigations demonstrate that performance of a concurrent task can affect many aspects of nonspeech motor control in individuals with PD, including gait, postural control, and upper extremity (e.g., manual) movement (e.g., Broeder et al., 2014; Dromey et al., 2010; Holmes et al., 2010; LaPointe et al., 2010; Marchese, Bove, & Abbruzzese, 2003; O'Shea et al., 2002; van Gemmert, Teulings, & Stelmach, 1998, 2001; Wu, Chan, & Hallett, 2010; Wu & Hallett, 2005; Wu et al., 2014). For example, Marchese et al. (2003) found that individuals with PD, but not controls, had a significant increase in center of foot pressure area when performing a postural task with concurrent cognitive and motor tasks compared to baseline. Relative to the dual-task effect on manual motor control, data suggest that motor deficits associated with micrographia worsen when individuals with PD perform handwriting movements under dual- compared to single-task conditions (Broeder et al., 2014; van Gemmert et al., 1998, 2001). For example, Broeder et al. (2014) found that individuals with PD exhibited smaller amplitudes of handwriting movements (e.g., successive cursive lowercase L) when performing a concurrent mental manipulation task than when performing handwriting movements in isolation. Comparable changes were not observed for control participants, suggesting that basic manual control in individuals with PD is more vulnerable to dual-task interference than in neurologically healthy controls (Broeder et al., 2014). Similar performance breakdowns under dual-task conditions have been observed when individuals with PD perform other types of manual tasks under dual-task conditions such as finger tapping (e.g., Wu et al., 2010, 2014; Wu & Hallett, 2005).

Other authors have examined the extent to which dual-task performances affects speech protection in individual with PD (e.g., Bunton & Keintz, 2008; Dromey et al., 2010; Ho et al., 2002; McCaig et al., 2016; Whitfield & Goberman, 2017b). For example, Dromey et al. (2010) found greater bidirectional dual-task interference in individuals with PD compared to healthy younger adults and age-matched controls when performing concurrent speech (i.e., sentence repetition task) and postural tasks. Performance changes between the single- and dual-task conditions included a decrease in the first and second formant extent and slope for diphthong formant trajectories and a decrease in postural stability, characterized by smaller, slower, and less stable movements during a rise-to-toe task (Dromey et al., 2010). Another study by McCaig et al. (2016) examined the effects of concurrent walking on speech intensity and speech rate during an extemporaneous speech task. The concurrent walking condition produced higher speech intensity in both the PD and control groups compared to standing and sitting conditions (McCaig et al., 2016). These findings suggest that there are bidirectional interactions between the speech system and control of posture and gait in individuals with PD (Dromey et al., 2010; Holmes et al., 2010; McCaig et al., 2016).

Although studies document that speakers with PD experience greater interference from secondary postural and gait tasks, the whole-body dynamic nature of these tasks may lead to muscular adjustments that impact the speech production mechanism (e.g., postural changes that affect muscles of the chest wall, abdomen, head, and neck).

However, other authors have documented interactions between concurrently performed speech and upper extremity tasks (S. G. Adams, Winnell, & Jog, 2010; Ho et al., 2002; Whitfield & Goberman, 2017b). Ho et al. (2002) found that participants with PD demonstrated a greater degree of dual-task interference than controls when a spontaneous conversation and a numerical recitation (i.e., counting) task were performed with a visuomotor task (i.e., counteracting movement on a visual display with a joystick). For the counting task, speakers with PD exhibited a lower mean speech intensity, a higher rate of speech intensity decay, and a slower rate between the single- and dual-task conditions (Ho et al., 2002). S. G. Adams et al. (2010) reported that speakers with PD exhibited an increase in speech intensity when concurrently performing a visuomotor grip control task, whereas controls exhibited a reduction in speech intensity from the single- to dual-task conditions. An investigation of speech motor sequence learning by Whitfield and Goberman (2017b) reported that speakers with PD exhibited greater bidirectional dual-task interference than healthy controls when a recently learned nonword sequence was performed with a concurrent visuomotor rotor pursuit task, which involved tracking an onscreen target moving along a circular path at a constant angular velocity using a computer mouse. Speakers with PD exhibited a significantly greater reduction in speaking rate and visuomotor task performance than controls, suggesting greater bidirectional dual-task interference (Whitfield & Goberman, 2017b). Together, these findings suggest that speakers with PD exhibit bidirectional dual-task performance degradation when a speaking task is performed with a secondary upper extremity motor task that requires the visual system (Ho et al., 2002; Whitfield & Goberman, 2017b).

Although prior research has documented the effects of attention-demanding upper extremity visuomotor tasks on speech production in speakers with PD, only one study to date has reported on the potential effects of a concurrent upper extremity motor task that requires minimal cognitive demand (i.e., Bunton & Keintz, 2008). That study examined the extent to which turning a nut on a bolt affected the speech of four individuals with PD and four controls. Changes in acoustic and perceptual measures of speech were observed that were indicative of worsening speech motor symptoms for speakers with PD (Bunton & Keintz, 2008). Given that individuals with PD exhibited changes in manual control under dual-task conditions (e.g., Broeder et al., 2014), these data suggest that speakers with PD may exhibit a pattern of bidirectional dual-task interference when speech production tasks are performed with a low-demand motor task. The implications of such a finding would suggest that the load of a simple manual task, requiring little to no attentional resources, disrupts speech production processes in individuals with PD. Documenting the effects of a concurrent low-demand secondary task on speech production would help to establish the baseline dual-task interference in speakers with PD. Quantifying baseline interference from simple secondary motor task holds important implications for understanding speech motor automaticity in PD (e.g., Wu et al., 2014) and for comparing to interference patterns observed for secondary tasks that require a greater attentional load, such as visuomotor tasks.

The purpose of the current investigation was to quantify baseline dual-task interference associated with concurrent performance of a low-demand manual task and connected speech tasks in individuals with and without PD. Participants with and without PD performed a continuous, counterclockwise circle-drawing task in isolation and while performing two connected speech tasks (i.e., reading a passage and producing extemporaneous, prompted speech samples). The circle-drawing task was chosen because it is a relatively simple motor task that requires only finger extension and flexion, and ulnar and radial deviation. Because of its simple motoric nature, the task can be performed relatively automatically, as it requires little to no attentional resources (e.g., Saltuklaroglu, Teulings, & Robbins, 2009). Additionally, manual movement associated with the motor task is less likely to affect musculature proximal to the elbow compared to tasks involving postural control, which may recruit the chest wall musculature. Similar tasks have been used in several dual-task studies that have examined upper extremity motor control (e.g., Saltuklaroglu et al., 2009; van Gemmert et al., 1998, 2001). The reading and extemporaneous speech tasks were chosen because they simulate a range of cognitive–linguistic demands required in everyday speaking situations and are often used in studies of dual-task performance (e.g., Ho et al., 2002; McCaig et al., 2016).

Kinematic measures from the oscillatory manual task were examined to quantify secondary task performance, because prior studies suggest performance of a secondary task affects manual kinematics (van Gemmert et al., 1998, 2001). Additionally, several acoustic measures of speech including vowel space, articulation rate, pause duration, fundamental frequency (F0) variation, and speech intensity were examined as prior work suggests that performance of a secondary task affects phonation, articulation, and speech prosody (e.g., S. G. Adams et al., 2010; Bunton & Keintz, 2008; Dromey et al., 2010; Ho et al., 2002). Kinematic changes in the manual task during concurrent speaking were expected for all participants as prior studies suggest that concurrent speaking affects handwriting kinematics (Saltuklaroglu et al., 2009; van Gemmert et al., 1998, 2001). Because the secondary motor task was selected to minimize attentional load, little to no changes in speech production measures were expected, especially for control speakers. Previous literature suggests, however, that speakers with PD are more susceptible to dual-task effects than controls (e.g., Dromey et al., 2010; Ho et al., 2002; Whitfield & Goberman, 2017b). Given the simple motoric nature of the secondary task and the findings from prior literature, two competing hypotheses were formed for the PD group: (a) Speakers with PD would exhibit little to no change in speech production during dual-task performance given the low attentional demands of the secondary task, and (b) speakers with PD would exhibit slight changes in speech production because they are more susceptible to dual-task interference than neurologically healthy controls.

Method

Participants

Twenty-three participants, 12 with PD (nine males, three females) and 11 neurologically healthy controls (two males, nine females), participated in the current study. The mean age of the participants in the PD group was 64 years (*SD* = 7.16 years, range: 53–75 years), and the mean age of the participants in the control group was 67 years (*SD* = 6.34 years; range: 54–75 years). Per self-report, all participants were right-handed. Participants completed a medical history form with information about illnesses, medication, and speech, language, hearing, or learning problems. Exclusionary criteria for controls included a self-reported neurological disorder; medication likely to affect speech, language, or cognitive performance (e.g., sedatives, anxiolytics, antipsychotics, stimulants); or reported deficits in speech, language, cognition, reading, or hearing.

Table 1 presents disease and dysarthria characteristics for the PD group. Inclusionary criteria for individuals in the PD group included a diagnosis of idiopathic PD from a neurologist trained as a movement disorders specialist. Speakers in the study completed screenings related to speech, language, hearing, and cognitive abilities. A certified speech-language pathologist rated dysarthria type and severity from recordings of three sustained vowels, alternating and sequential motion rate tasks, and a reading of the Rainbow Passage (Fairbanks, 1960). To differentially diagnose dysarthria type and severity, deviant speech characteristics were identified and rated using Mayo Clinic assessments (e.g., Darley et al., 1969). The mean disease duration for the PD group was 6 years (range: 2;4 [years; months] to 16 years). All patients had seen a neurologist within the past 9 months and were taking dopaminergic medication for the symptomatic treatment of PD. No participant in the PD group had received a deep brain stimulation implant. At the time of participation, all speakers with PD were reported being in the "on" medication state, and all participants indicated that they did not experience fluctuations in medication effectiveness. Part III of the Unified Parkinson Disease Rating Scale (Goetz et al., 2008) was administered to characterize motor deficits of participants in the PD group on the day of data collection by an experimenter trained in the administration of the exam. The Hoehn and Yahr scale was used to describe disease progression in the sample.

To screen cognitive function, all participants completed the Montreal Cognitive Assessment (MoCA), which is a brief cognitive screening tool for mild cognitive impairment (MCI) that has been used to quantify cognitive function in PD (Dong et al., 2012; Nazem et al., 2009). A MoCA score ≥ 26 is indicative of typical cognitive functioning, whereas a score < 26 may indicate possible MCI. As reported in Table 2, the mean MoCA score for the participants in the PD group was 25.75 (range: 21–30), with six individuals in the MCI range, and the mean score for the participants in the control group was 27.55 (range: 23–30), with one individual scoring in the MCI range. Additional measures of cognitive–linguistic function included the digit span forward and backward as a measure of working memory; the Wechsler Test of Adult Reading (Wechsler, 2001), which provides a measure of intelligence; and the Shipley Vocabulary Test (Shipley, 1940). The means and standard deviations for these assessments are reported in Table 2. A series of independent-samples *t* tests ($p > .05$) revealed no between-group statistical differences in scores for the MoCA, forward span, backward span, Wechsler Test of Adult Reading, or Shipley Vocabulary Test.

Experimental Task Descriptions

After completing the informed consent process, demographic interview, and cognitive screening tasks,

Table 1. Participant demographics and cognitive screening scores for individuals in the Parkinson disease (PD) group.

ID	Sex	Age (yrs)	Disease duration (yrs)	UPDRS: Part III	H&Y stage	MoCA	WTAR	Shipley	Digit span		Dysarthria severity
									Forward	Backward	
PD01	M	53	8	28	1.5	26	105	33	8	4	Mild
PD02	M	71	16	55	3	27	105	32	8	5	Severe
PD03	F	63	2	36	3	24	111	34	7	5	Moderate
PD04	M	69	3	43	3	25	117	35	7	5	Moderate
PD05	F	60	7.5	32	2	30	102	29	7	5	Moderate
PD06	M	56	7.5	34	2	30	119	35	8	7	Moderate to severe
PD07	M	56	15	38	2	29	87	24	6	5	Moderate
PD08	M	66	4.5	43	2.5	24	98	32	5	5	Mild
PD09	F	64	4.5	40	3	26	111	30	6	4	Moderate
PD10	M	64	3	32	2	23	114	28	8	4	Moderate
PD11	M	74	2.5	41	2	21	98	29	6	4	Moderate to severe
PD12	M	75	2	31	3	24	99	29	6	4	Moderate

Note. ID = participant code; yrs = years; UPDRS = Unified Parkinson Disease Rating Scale; H&Y = Hoehn and Yahr; MoCA = Montreal Cognitive Assessment; WTAR = Wechsler Test of Adult Reading; Shipley = Shipley Vocabulary Test.

Table 2. Means (*M*) and standard deviations (*SD*) for the cognitive screening tasks demonstrate no statistically significant differences between groups for any measure.

	Control group		PD group	
Cognitive screenings	***M***	***SD***	***M***	***SD***
MoCA	27.55	2.16	25.75	2.83
WTAR	109.00	9.38	105.50	9.33
Shipley Vocabulary Test	34.00	2.19	30.83	3.27
Digit span forward	6.45	1.03	6.83	1.03
Digit span backward	5.09	1.14	4.75	0.87

Note. PD = Parkinson disease; MoCA = Montreal Cognitive Assessment; WTAR = Wechsler Test of Adult Reading.

participants completed two different speaking tasks—paragraph reading and an extemporaneous speech task for which they were prompted to talk about a topic for several minutes. The reading passages consisted of the Rainbow Passage (Fairbanks, 1960) and the John Passage (Tjaden & Wilding, 2004). Prompts for the extemporaneous speaking tasks were adapted from prior work by Kemper, Hoffman, Schmalzried, Herman, and Kieweg (2011). Previous investigations suggest that these prompts elicit comparable linguistic output and have been used to examine the effect of dual-task performance on extemporaneous speech (e.g., Kemper, Herman, & Lian, 2003; Kemper et al., 2009). The prompts included "Please describe someone you admire or someone who has influenced your life and why you admire them," "Who was the greatest president of the USA and why?", "What was the most significant invention of the 20th century and how does it affect your life?", and "What do you like most about living in your town? What do you like the least?". Participants were asked to answer the prompts in as much detail as possible. In the case that a participant did not have much to say on a particular prompt, a topic such as a recent holiday, family vacation, or hobby was cooperatively determined with the participant. Participants were familiarized with the four prompts before completion of the experimental protocol. The order of the extemporaneous speaking prompts was randomized between participants.

The secondary, oscillatory motor task was a low-demand, continuous, counterclockwise circle-drawing task using the dominant hand. Similar continuous handwriting and handwriting-like tasks have been used in investigations of handwriting performance (e.g., Teulings, Contreras-Vidal, Stelmach, & Adler, 1997). Participants were instructed to anchor the dominant wrist on the corner of the tablet while gripping the stylus as would be typical when writing. This instruction was given so that the circular movement would primarily result from finger extension and flexion (anterior/posterior dimension on the digitizer tablet) and ulnar and radial deviation (medial/lateral dimension on the digitizer tablet). Participants were asked to draw continuous circles of a comfortable circumference and a comfortable, but sufficiently fast, rate such that the circle drawing was relatively automatic. For each trial, participants were instructed to maintain contact between the stylus and tablet and to continue drawing circles until signaled by the researcher.

Data Collection Setup

Participants were fitted with a head-mounted microphone (Shure Beta 53, Shure Incorporated) to record the speech samples in a sound-attenuated booth. The speech samples were captured using a computer that was located outside the booth. The microphone signals were digitized using a high-quality USB sound card with preamplifiers (RME Fireface UCX; sampling rate: 44.1 kHz) and were recorded as .wav files using Adobe Audition. Inside the sound booth, a computer and a large tablet (Large Wacom Tablet, Wacom; dimensions: 32.51 × 20.32 cm; resolution: 5.0×10^{-4} cm) with a stylus (Wacom Grip Pen) were positioned in front of each participant for experimental presentation and manual movement data collection. Tones generated from the presentation computer inside the booth marked the beginning and end of each experimental trial and were recorded onto a second channel of the USB sound card. The microphone gain levels were set for each participant. Participants were instructed to speak at a comfortable rate and loudness level as if they were having a conversation with another person. Data from the tablet were collected in MovalyzeR (NeuroScript; sampling rate: 132 Hz).

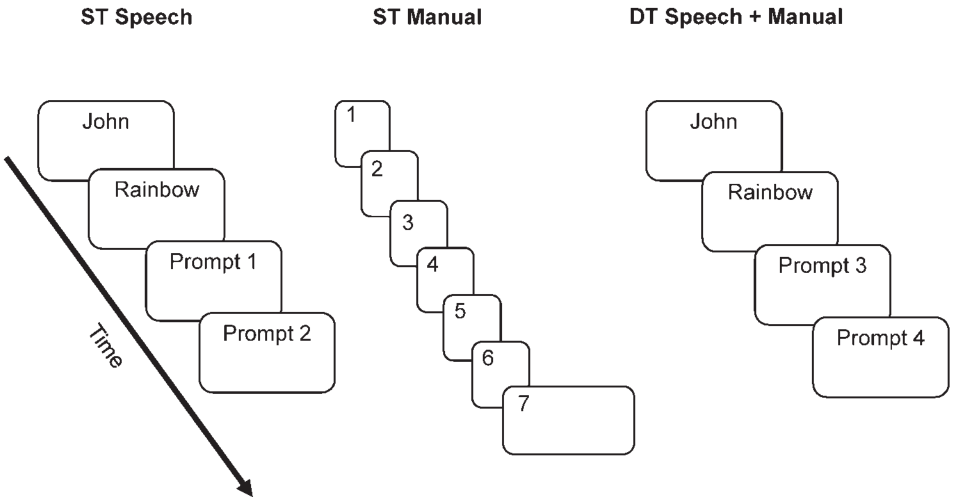
Experimental Protocol

Figure 1 shows a visual representation of the experimental protocol. Each of the three tasks (i.e., reading task, extemporaneous speech task, and oscillatory manual task) was first performed in isolation (i.e., single-task conditions), and then the speaking tasks were each performed concurrently with the manual task (i.e., dual-task conditions). For the single-task block, speakers read the Rainbow Passage and the John Passage aloud in the single-task condition. Then, the experimenter presented an extemporaneous prompt followed by the participant's response and repeated this procedure for a second prompt. The participant then completed six, 15-s manual task trials in isolation, which served as practice or familiarization trials. After the six practice trials of the manual task, the participants completed one longer single-task trial of the circle-drawing task that was comparable in duration to the extemporaneous speech samples produced in the single-task condition. Participants then moved into the dual-task blocks. First, participants produced the same two readings while performing the manual task. Participants then produced two additional extemporaneous speech samples while performing the manual task concurrently.

Manual Kinematic Measures

Several kinematic measures of digitized stylus movements were examined to quantify manual task performance

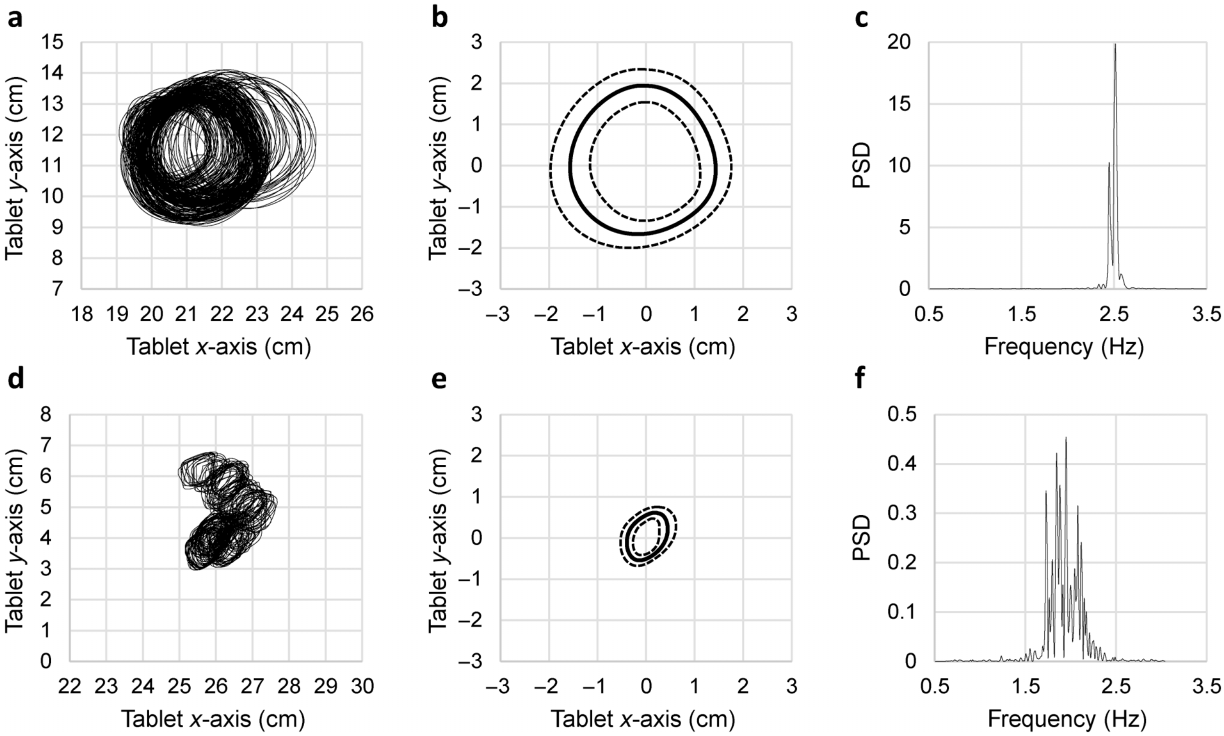
Figure 1. Visual representation of the experimental protocol depicting the sequence of task starting with the single-task (ST) speech trials, then the ST manual task trials, and ending with the dual-task (DT) trials. Note that "Rainbow" and "John" indicate the reading passages and "Prompt" indicates the prompts given to elicit the extemporaneous speech tasks, the order of which was randomized across participants. The final ST manual trial was used as the ST referent and was comparable in duration to the ST speaking tasks.



in the single- and dual-task conditions. The digitized traces from the manual task trials were processed and analyzed in custom software developed using NI LabVIEW 2016 (National Instruments Corp.). Furthermore, manual trials were analyzed both in whole and with respect to mean circle cycle characteristics. To identify individual circle cycles throughout each trial, the y-position data were first high-pass filtered using a fourth-order, phase-neutral Butterworth filter with a 0.1-Hz cutoff. This step effectively removed low-frequency oscillation (aka *wandering baseline*) from the signal to facilitate the identification of y-position local maxima. Additionally, the high-pass filter served to reorient the y-position waveform baseline to zero, which was subsequently used as the threshold for peak detection. Next, y-coordinate maxima were identified, establishing the transition from stylus movement in the positive y-direction to movement in the negative y-direction at the end of a previous circle cycle and the beginning of the next. While processed y-coordinate data were employed to identify cycle events, the event indices were then applied to parse both the raw x- and y-coordinate time series. Once a trial was cut into individual circle cycles, the mean x and y coordinates from each cycle were subtracted from all cycle positions to translate each circle trace to an origin at (0, 0). Figure 2 depicts an example of the raw manual trace (left panels), as well as the recentered circle cycles' mean with ± 2-*SD* error bands (middle panels). For simplicity, vertical and horizontal handwriting kinematics were analyzed collectively by evaluating the radial characteristics of the circular cycles within each trial. First, a mean cycle was calculated by averaging the radii (in centimeters) of all cycle segments falling within 10°, overlapping windows throughout the full 360° range. Then, mean trial kinematic magnitude was determined by averaging the radii from the mean cycle. Within-trial kinematic variation was calculated by first computing the standard deviations of all cycle radii within the 10° windows, and then the standard deviations from each window were averaged to arrive at an aggregate variance metric. A visual representation of the kinematic range of motion/variance algorithm is provided in Supplemental Materials S1–S3.

A fast Fourier transform was applied to the horizontal and vertical movement time series in order to compute the linear power spectral density (PSD) profile associated with each manual task trial. The spectral characteristics of the horizontal and vertical movement dimensions were nearly identical (typical of inherent two-dimensional coupling), so only the vertical-direction spectral findings are presented. As with the spatial exemplars, manual trial movement spectra for a control participant and a participant with PD are displayed in Figure 2 (right panels). To characterize movement, the dominant spectral frequency was estimated by identifying the frequency associated with the greatest relative power (e.g., 1.95 Hz in Figure 2f). Additionally, the median frequency was identified by determining the frequency that evenly divided the area under the PSD waveform, with 50% of the area below and 50% above the specified frequency. To estimate spectral variation within the manual trace trials, an iterative optimization algorithm was applied, which created successively larger frequency windows, centered at the median frequency, until the range associated with 90% of the area under the PSD waveform was identified (e.g., 0.65-Hz range about the median frequency at 1.94 Hz in Figure 2f). The 90% spectral range is reflective of the extent to which the movement frequencies were centralized, indicating relatively consistent movement velocity over the course of the trial, versus movement spectra of increased range, indicating increased

Figure 2. Example handwriting traces for one control participant (top panels) and one participant with Parkinson disease (bottom panels). The left panels show the raw tablet traces. The middle panels show the centered traces (dashed lines indicate ± 2 *SD*s from the mean centered trace). The right panels show the power spectral density (PSD) of the *y*-axis movement traces demonstrating the dominant spectral frequency and variation in the spectral peak.



variation in movement velocities. Examples of single-task videos showing the movement trace over time for a portion of these trials are available in Supplemental Materials S1–S3.

Speech Acoustics

Articulatory–Acoustic Vowel Space

To examine acoustic changes in speech articulation related to formant space, the articulatory–acoustic vowel space (AAVS; Whitfield & Goberman, 2014, 2017a) of each speech sample was computed from a processed continuous formant trace extracted from each sample. The AAVS was selected because it is a measure of working formant space that has been shown to be more sensitive to between-group differences and within-talker changes in vowel articulation than traditional point-based vowel space metrics for both healthy talkers (Whitfield, Dromey, & Palmer, 2018; Whitfield & Goberman, 2017a) and speakers with PD (Whitfield & Goberman, 2014; Whitfield & Mehta, 2019). Additionally, a recent investigation suggests that within-participant changes in the AAVS are moderately to strongly correlated with within-participant changes in a comparable measure of lingual range of motion (Whitfield et al., 2018).

A Kalman-based autoregressive approach consisting of preprocessing, intraframe observations, and interframe tracking was used to extract time series of the first three formant frequencies (F1, F2, and F3) from each of the speech samples (Mehta, Rudoy, & Wolfe, 2012). The preprocessing stage involved resampling the acoustic waveform to 7000 Hz to track three formants within a 3500-Hz bandwidth. After the waveform was resampled, it was segmented into 20-ms Hamming-windowed frames with 50% overlap. Each frame was then filtered using a first-order difference equation with a preemphasis coefficient of 0.95. In the intraframe observation stage, each frame was modeled as a stochastic autoregressive process with 12 linear predictive coding spectral coefficients that were transformed to 15 cepstral coefficients. The cepstral coefficients were mapped as observations in a state-space framework. Finally, the first three formant frequencies were derived as a linearized mapping of the cepstral coefficients using an extended Kalman smoother to complete the interframe tracking. The applied formant tracker provided well-behaved time series that were smoothly interpolated through non-speech frames.

After formant extraction, the formant frequencies were processed and filtered using a custom MATLAB script. The F1–F2 pairs, along with the corresponding time stamps, were imported into MATLAB. For each sample, the Praat-based PointProcess function was used to identify voiced frames when the F0 was reported by Praat (maximum period = 20 ms). Voiced intervals derived in

Praat were used to segment the formant trajectories for analysis. For each voiced interval, local outliers in the formant trace were removed using a median absolute deviation moving average function in MATLAB and the resulting trace was low-pass filtered at 10 Hz. Bivariate outliers in the filtered formant trajectory, defined as an F1–F2 greater than 2 *SD*s from the centroid using Mahalanobis distance, were removed from the traces. For the current study, the AAVS was calculated for each connected speech sample produced by the participants. The sample level AAVS was calculated as the square root of the generalized variance of the F1 and F2 formant data, which is calculated as the product of the F1 variance, F2 variance, and proportion of the unshared variance between F1 and F2 (see Whitfield & Goberman, 2014, 2017a). The AAVS is a measure of working vowel space that represents a bivariate standard deviation in the F1–F2 space and is expressed in square hertz.

Speech Rate Measures

To examine articulatory and prosodic aspects of speech rate and time, articulation rate and mean pause duration were examined separately. Each sound file was visualized using a spectrogram display (Praat) and automatically segmented into sounding intervals (lasting at least 50 ms) and silent intervals (lasting at least 150 ms). Automatically generated interval boundaries were manually adjusted to ensure that the alignment was accurate.

Articulation rate was calculated within each sounding interval as the number of syllables divided by the sounding interval duration to examine the rate of syllable production irrespective of pause. In contrast to traditional measures of speech rate, articulation rate quantified the rate of syllable articulation that was decoupled from the influence of pause time, which is associated with prosodic aspects of speech rate (e.g., Goberman, Coelho, & Robb, 2005; Tjaden & Wilding, 2011).

Pause duration was also measured for all silent intervals that were not associated with stop consonant production to examine prosodic timing. Silent intervals associated with consonant production (e.g., stop gaps) were manually identified and excluded. For this process, intervals that were near the 150-ms cutoff were examined relative to the surrounding phonetic environment. Short intervals that were followed by a subsequent stop consonant were considered articulatory in nature and were thus considered to be part of the spoken interval. Removal of pause intervals was rare, as less than 3% of the labeled intervals initially labeled as pause were removed.

Speech Intensity

Speech intensity was estimated to acoustically quantify aspects of speech production related to loudness. After each experimental run, the microphone signal was calibrated to calculate speech intensity offline. A complex auditory tone from a loud speaker was used to calibrate the microphone signal. The complex auditory tone (100-Hz triangle wave) was recorded using the microphone and a calibrated sound level meter (SLM; M3 Model 1100, Question Technologies) at a 5-cm distance to equate the Praat-based intensity of the microphone signal to the SLM intensity. Mean intensity of each sounding interval was calculated using Praat. These Praat-based intensities were adjusted by the difference between the Praat-based intensity and the SLM intensity to obtain an estimate of speech intensity in dB SPL. Calibration procedures aligned with Method 2A outlined by Švec and Granqvist (2018).

F0 Variability

F0 variability was calculated to examine phonatory–prosodic characteristics of speech production. F0 contours were extracted from each sample using a Praat-based algorithm, which uses a forward cross-correlation analysis to perform an acoustic periodicity detection (time step = 0.003 s). The F0 contour of each sample was visually inspected before running the analyses to determine an appropriate pitch range for each participant. Finally, the F0 variability was computed for each sounding interval as the standard deviation of the F0 contour (F0SD), in semitones. The standard deviation was first derived in hertz and then converted to semitones with the mean F0 of the segment as a referent.

Statistics

Linear mixed models (LMMs) were constructed to examine changes in the kinematic measures of the manual task and acoustic measures of the speech tasks. The LMM analyses allow researchers to specify an individual participant with several observations of the dependent variables for each condition and characterize the effect of condition (single task vs. dual task), as well as the nested unbalanced effect of task (single task, dual task with reading, dual task with extemporaneous speech). For the dependent variables of the manual task (i.e., mean radius, variation in the mean radius, dominant spectral frequency, and spectral variation), models were constructed to examine the main effect of group (control vs. PD) and condition (single task vs. dual task), as well as the associated interaction. Speaking task (reading vs. extemporaneous) was nested within condition. For these models, trial number and participant were modeled as random slope and intercept terms, respectively. The intercepts were mapped to the values for the single-task condition performed by the control group. For the speaking tasks, the mean AAVS, articulation rate, pause duration, speech intensity, and F0SD were computed for each speaking task (reading and extemporaneous) and each condition (single task and dual task). Models were constructed for each dependent variable to examine the fixed effects of group (control vs. PD), condition (single task vs. dual task), and sex, as well as the Group × Condition, Group × Task, Condition × Task, and Group × Task × Condition interaction effects. For these models, the random-effect structure included speaking task and condition as random slope terms and participant as a random intercept term. The intercepts of these models were mapped to the values for the single-task reading produced by the control group. Sex was coded as a ratio level variable and was centered around zero so that the intercept and parameter estimates represented the mean value across all participants. Sex was modeled as a fixed effect and not crossed with other variables to account for variation associated with sex, regardless of group membership, speaking task, or condition. All fixed effects and parameter estimates were examined using an α (significance) criterion of .05. Standard data screening procedures were completed by examining residual plots for each model.

Results

Table 3 summarizes the durations of the single- and dual-task trials for each subject group. A series of independent-samples *t* tests revealed that there were no between-group differences in duration for the single-task speech, single-task manual, or dual-task trials ($p > .05$) for all comparisons. Paired *t* tests revealed that there were no differences between the duration of the single-task manual trial and the dual-task trial durations for either group, $p > .05$. Thus, the experimental conditions were relatively equal across all participants and tasks, as comparison of trial durations revealed no differences between or within groups.

Manual Task Kinematics

Figure 3 shows means and standard error for the kinematic metrics of the secondary oscillatory manual task for each group, condition, and task. Parameter estimates for the various manual task metrics are reported in Table 4. Relative to the mean radius, results revealed a significant main effect of group, suggesting individuals with PD exhibited significantly smaller circles regardless of condition, $F(1, 18.65) = 9.838$, $p = .005$ (see Figure 3). Main effects of condition were not observed, $p > .05$. A significant three-way interaction, $F(1, 48.08) = 5.479$, $p = .007$, suggested that, in the dual-task condition, participants exhibited a larger mean radius when performing the extemporaneous speaking task compared to the reading task, $p = .003$. This pattern did not differ between speakers with PD and controls, $p > .05$ (see Figure 3).

Table 3. Sample durations (mean [*M*] and standard deviation [*SD*]), in seconds, demonstrate no statistically significant between-group differences for each task.

	Control group		Parkinson disease group	
Task	***M***	***SD***	***M***	***SD***
ST reading	80.8	18.8	89.2	30.1
ST extemporaneous	97.0	55.0	87.0	38.7
ST manual	86.9	35.6	79.2	33.8
DT reading	80.3	19.4	80.7	26.4
DT extemporaneous	94.0	30.5	82.3	32.4

Note. ST = single task; DT = dual task.

Results for the intratrial variation in mean radius revealed a significant Group × Condition interaction, $F(1, 35.80) = 5.924$, $p = .020$, and a Group × Condition × Speaking Task interaction, $F(1, 450.54) = 4.179$, $p = .0201$. Parameter estimates revealed that control participants exhibited a very slight decrease in the average variation of the mean radius, $p = .044$, compared to the single-task condition. Conversely, participants with PD exhibited an increase in average variation of the mean radius from the single- to dual-task conditions, $p = .005$ (see Figure 3). When the manual task was performed concurrently with the extemporaneous speech task, control participants exhibited an increase in variability in the mean radius, $p = .009$ (see Figure 3).

Results for the peak movement frequency in the manual trace revealed a main effect of condition, $F(1, 51.87) = 4.553$, $p = .038$, and a significant Group × Condition interaction, $F(1, 51.87) = 6.544$, $p = .013$. Parameter estimates revealed a Group × Condition interaction for which dominant spectral frequency decreased in the dual-task condition for control participants, $p = .006$. Within the dual-task condition, control participants exhibited a slight decrease dominant spectral frequency between the dual-task reading and extemporaneous speech task, $p = .046$. Results for the spectral variation in the manual trace revealed fixed effects of group, $F(1, 18.86) = 10.77$, $p = .004$, and condition, $F(1, 64.54) = 18.400$, $p < .001$, as well as a significant Group × Condition interaction, $F(1, 64.54) = 5.156$, $p = .027$. As seen in Figure 3, individuals with PD exhibited more spectral variation in the movement trace than controls. Parameter estimates revealed that speakers with PD exhibited a greater increase in spectral variation between the single- and dual-task conditions than controls, $p = .016$. No differences in spectral variation were observed between concurrent reading and extemporaneous speech for either group, $p > .05$.

Speech Task Measures

Although the extemporaneous prompts were randomized between participants to control for potential differences between each, preliminary analyses were conducted to ensure that there were no statistical differences for the five acoustic variables associated with the prompts used to elicit the extemporaneous speaking task. Five one-way repeated-measures analyses of variance were constructed using the mean articulation rate, pause duration, and AAVS for each prompt. The main effect of prompt was not statistically significant for any of the dependent variables, $p > .05$ for all contrasts. Thus, the specific prompts used to elicit extemporaneous speech did not systematically affect the acoustic variables. Therefore, the data from each extemporaneous speech sampled were pooled for the subsequent analyses.

Figure 4 shows the means and standard error for the acoustic measures examined in the reading and extemporaneous tasks. Additionally, the fixed effect parameter

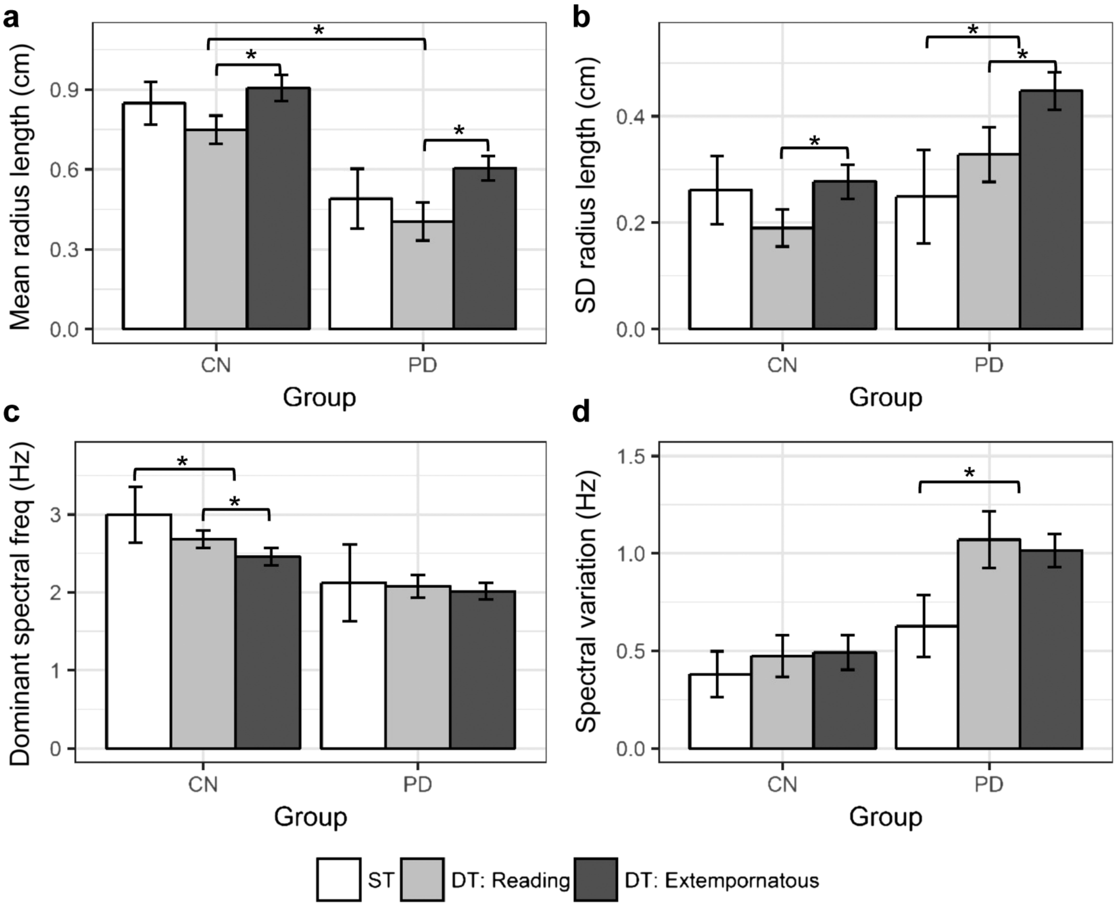


Figure 3. Kinematic variables for the oscillatory manual task including the (a) mean length and (b) standard deviation (*SD*) in radius, (c) dominant spectral frequency (freq), and (d) 90% area under the curve of the movement spectrum (spectral variation) for neurologically healthy controls (CN) and participants with Parkinson disease (PD) in the single-task (ST; white fill) and dual-task (DT; gray fill) conditions. “Reading” and “Extemporaneous” indicate the dual-task conditions associated with concurrent performance in the reading and extemporaneous speech tasks, respectively. Error bars represent standard error. $^*p < .05$.

estimates of the LMM analyses for the acoustic variables are displayed in Table 5.

AAVS

Results for the LMM for the AAVS revealed a fixed effect of group, $F(1, 22.65) = 5.688$, $p = .026$ (see Figure 4a). The fixed effects of speaking task (reading vs. extemporaneous), condition (single task vs. dual task), sex, Group × Task interaction, Group × Condition interaction, and Group × Speaking Task × Condition interaction were not statistically significant, $p > .05$. Parameter effect estimates revealed that the speakers with PD exhibited a slightly smaller AAVS. Though not statistically significant, AAVS was, on average, lower for male compared to female speakers, $p = .074$ (see Table 5). Random effects revealed that there was significant variation between participants in the AAVS between the reading and extemporaneous tasks, $\chi^2(3) = 8.30$, $p < .040$, but not the single- and dual-task conditions, $p = .08$. Percent change from the single- to dual-task conditions was quantified to measure cost associated with concurrent task performance. For the reading task, the percent change in the AAVS from the single- to dual-task conditions ranged from −0.1% to 6.9% for the control group, with an average absolute change of 2.9%. The percent change in the AAVS for the PD group for the reading task ranged from −20.4% to 5.3%, with an average absolute change of 5.1%. For the extemporaneous task, the percent change in the AAVS from the single- to dual-task conditions for the control group ranged from −11.4% to 26.5%, with an average absolute percent change of 8.4%. For the PD group, the percent change in the AAVS for the extemporaneous task ranged from −22.5% to 21.7%, with an average absolute change of 10.9%.

Articulation Rate

Results for the LMM for articulation rate revealed fixed effects of group, $F(1, 23) = 4.471$, $p = .045$, speaking task, $F(1, 23) = 24.630$, $p < .001$, and sex, $F(1, 23) = 4.955$, $p = .0361$. Examination of Figure 4b demonstrates that speakers with PD exhibited slightly faster articulation rates

Table 4. Fixed-effects parameter estimates for the linear mixed models for the manual kinematic variables.

Model	*b*	*SE*	*df*	*t*	*p*
ROM (mean circle radii; cm)					
Intercept	0.849	0.081	19.3	10.489	< .001***
Group (PD)	–0.358	0.112	18.0	–3.200	.005**
Condition (DT)	–0.099	0.053	68.1	–1.869	.066
Group (PD) × Condition	0.013	0.071	66.6	0.181	.857
Group (CN) × Condition (E)	0.156	0.049	49.2	3.168	.003**
Group (PD) × Condition (E)	0.043	0.045	47.0	0.959	.343
SD in ROM (*SD* of circle radii; cm)					
Intercept	0.261	0.064	19.78	4.113	< .001***
Group (PD)	–0.012	0.088	19.86	–0.138	.892
Condition (DT)	–0.071	0.035	66.45	–2.054	.044*
Group (PD) × Condition	0.150	0.051	68.21	2.931	.005**
Group (CN) × Condition (E)	0.087	0.032	45.29	2.741	.009**
Group (PD) × Condition (E)	0.032	0.035	57.23	0.918	.363
Dominant spectral frequency (Hz)					
Intercept	2.996	0.356	20.56	8.412	< .001***
Group (PD)	–0.875	0.491	20.52	–1.783	.089
Condition (DT)	–0.312	0.109	74.06	–2.849	.006**
Group (PD) × Condition	0.268	0.149	74.27	1.802	.076
Group (CN) × Condition (E)	–0.226	0.111	62.12	–2.036	.046*
Group (PD) × Condition (E)	0.164	0.107	60.56	1.531	.131
Spectral variation (Hz)					
Intercept	0.381	0.119	29.030	3.196	.003**
Group (PD)	0.246	0.163	27.750	1.515	.141
Condition (DT)	0.127	0.102	65.650	1.249	.216
Group (PD) × Condition	0.346	0.140	65.850	2.468	.016*
Group (CN) × Condition (E)	0.005	0.081	65.200	0.063	.950
Group (PD) × Condition (E)	–0.101	0.083	67.000	–1.223	.226

Note. The intercept is mapped to the control group in the single-task condition. ROM = range of motion; PD = Parkinson disease; DT = dual task; CN = control group; E = extemporaneous.

$^{*}p < .05$. $^{**}p < .01$. $^{***}p < .001$.

than controls. Examination of parameter estimates revealed that articulation rates for the extemporaneous task were significantly slower than articulation rates for the reading task, $p = .007$ (see Table 5). Additionally, parameter estimates revealed that female speakers exhibited a slightly faster articulation rate than did male speakers, $p = .036$. All other fixed effects were not statistically significant, $p > .05$ for all contrasts. Random effects suggested significant differences in variation among participants in articulation rate between speaking tasks, $\chi^2(2) = 24.740$, $p < .001$, but not between the single- and dual-task conditions, $p > .60$.

Pause Duration

Results for pause duration revealed significant fixed effects of group, $F(1, 26.67) = 8.839$, $p = .006$, and speaking task, $F(1, 23.11) = 33.625$, $p < .001$, that were qualified by significant Group × Condition, $F(1, 24.02) = 7.038$, $p = .014$, Group × Speaking Task, $F(1, 23.11) = 6.895$, $p = .015$, and Group × Condition × Speaking Task, $F(1, 45.61) = 7.531$, $p = .009$, interactions. Parameter estimates revealed that speakers with PD exhibited significantly longer pause duration in the extemporaneous task compared to the reading task, $p = .001$ (see Table 5). Estimates suggest that the mean pause duration in the single-task extemporaneous speaking task for speakers in the PD group was 72.3% longer than the mean pause duration for the control speakers (see Figure 4c). Additionally, speakers with PD exhibited a substantial reduction in pause duration between the single- and dual-task conditions when performing the extemporaneous task, $p = .009$. Comparison of the parameter estimates suggests that speakers with PD exhibited an 18.4% reduction in pause duration between the single- and dual-task conditions (see Figure 4c). This trend was not observed for control speakers, $p = .320$. Random effects suggested significant variation between participants in pause duration between the reading and extemporaneous tasks, $\chi^2(3) = 42.69$, $p < .001$, but not between the single- and dual-task conditions, $p = .50$.

Speech Intensity

Results for speaking intensity revealed an effect of speaking task, $F(1, 23.00) = 6.105$, $p = .021$. The effects of group, sex, and condition, as well as the interaction effects, were not significant, $p > .05$ for all contrasts. Examination of the parameter estimates revealed no difference between the two speaking tasks, on average, $p = .513$ (see Table 5). Random effects revealed significant variation between participants in intensity between the extemporaneous and reading tasks, $\chi^2(3) = 8.64$, $p = .030$, and between the single- and dual-task conditions, $\chi^2(3) = 30.11$, $p < .001$.

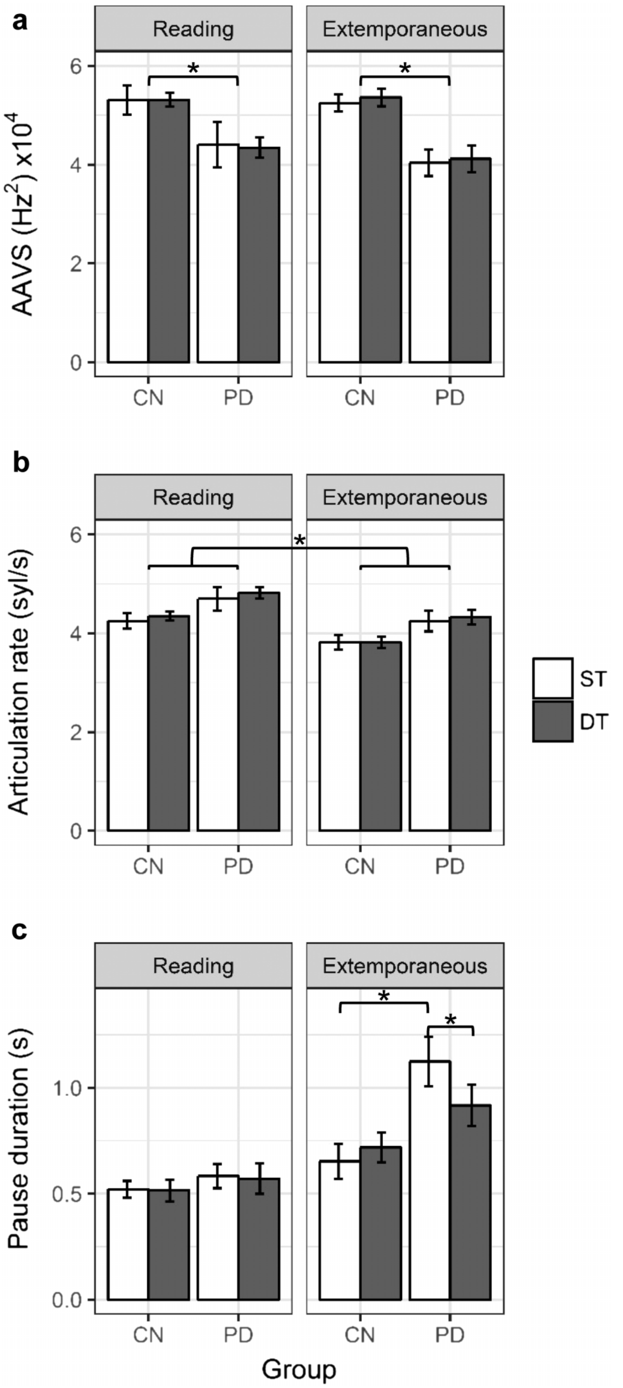


Figure 4. Acoustic variables for the reading and extemporaneous speech tasks including the (a) articulatory–acoustic vowel space (AAVS), (b) articulation rate in syllables per second (syl/s), and (c) mean pause duration for neurologically healthy controls (CN) and participants with Parkinson disease (PD) in the single-task (ST; white fill) and dual-task (DT; gray fill) conditions. Error bars represent standard error. *$p < .01$.

F0 Variability

Results for the F0SD model revealed that the fixed effects of group, speaking task, condition, and sex, as well as all interaction effects, were not statistically significant, $p > .05$, for all comparisons. Random effects revealed significant variation between participants in F0SD between the extemporaneous and reading tasks, $\chi^2(3) = 29.917$, $p < .001$, but not between the single- and dual-task conditions, $p = .90$.

Discussion

The purpose of the current investigation was to quantify baseline dual-task interference associated with concurrent performance of a low-demand manual task and connected speech tasks in individuals with and without PD. Participants with and without PD performed an oscillatory manual task (i.e., drawing continuous counterclockwise circles) while producing reading passages and extemporaneous speech. The oscillatory manual and speaking tasks were also performed in isolation. Relative to manual task performance, both individuals with PD and control participants exhibited changes in manual kinematics under dual-task conditions. Metrics characterizing intratrial variability in manual movement revealed that speakers with PD exhibited an increase in movement variation in the dual-task condition, regardless of speaking task. Controls exhibited changes in movement variability when concurrently performing the extemporaneous task, but not the reading task. For the reading task, no changes in the speech production variables were observed for either group, suggesting that the low-demand manual task did not interfere with speech production processes. Relative to speech task performance, neither group exhibited changes in any of the acoustic measures when the reading task was performed with concurrent circle drawing, compared to reading alone. For the extemporaneous task, speakers with PD exhibited a substantial decrease in pause duration from the single- to dual-task conditions, whereas control speakers exhibited little to no change in pause duration from the single- to dual-task conditions. Overall, concurrent performance of a low-demand motor task produced little to no effects on speech production. However, performance of a simple manual task affected pause duration in the extemporaneous speech production in individuals with PD, whereas no changes in speech where observed for age-matched controls during concurrent task performance.

Manual Task Performance

The current study examined manual kinematics associated with single- and dual-task performance of an oscillatory manual task that involved drawing continuous counterclockwise circles. Regardless of condition, individuals with PD exhibited a significantly smaller mean radius than controls. Prior work examining similar manual oscillatory tasks and handwriting movements have reported that individuals with PD often exhibit a significantly smaller range of motion

Table 5. Fixed-effects parameter estimates for the linear mixed models for the acoustic variables.

Model	Estimate	*SE*	*df*	*t*	*p*
AAVS (Hz^2)					
Intercept	53106.31	2991.29	22.12	17.75	< .001**
Group (PD)	−9067.14	4573.93	22.74	−1.98	.060
Condition (DT)	31.72	1395.87	12.69	0.02	.982
Speaking task (E)	−623.21	1771.92	28.94	−0.35	.728
Sex	7705.02	4068.94	18.68	1.89	.074
Group × Condition	−644.62	2072.20	12.59	−0.31	.761
Group × Speaking Task	−3053.03	2641.17	28.96	−1.16	.257
Condition × Speaking Task	1116.76	1802.04	9.72	0.62	.550
Group × Speaking Task × Condition	297.56	2684.83	9.74	0.11	.914
Articulation rate (syllables/s)					
Intercept	4.25	0.16	25.99	26.20	< .001**
Group (PD)	0.45	0.24	26.33	1.90	.068
Condition (DT)	0.10	0.09	45.01	1.14	.260
Speaking task (E)	−0.43	0.15	30.14	−2.88	.007*
Sex	0.48	0.22	23.00	2.23	.036*
Group × Condition	0.02	0.12	45.01	0.15	.882
Group × Speaking Task	−0.02	0.21	30.14	−0.09	.928
Condition × Speaking Task	−0.10	0.11	23.00	−0.92	.366
Group × Speaking Task × Condition	0.06	0.15	23.00	0.36	.724
Pause duration (ms)					
Intercept	520.55	39.88	43.49	13.05	< .001**
Group (PD)	62.95	57.16	44.22	1.10	.277
Condition (DT)	−4.44	51.77	50.58	−0.09	.932
Speaking task (E)	131.95	83.66	32.48	1.58	.124
Sex	−59.98	43.85	26.61	−1.37	.183
Group × Condition	−8.01	71.67	50.58	−0.11	.911
Group × Speaking Task	408.95	115.82	32.48	3.53	.001*
Condition × Speaking Task	70.11	69.75	45.61	1.01	.320
Group × Speaking Task × Condition	−265.01	96.57	45.61	−2.74	.009*
Speech intensity (dB)					
Intercept	57.64	2.70	24.32	21.39	< .001**
Group (PD)	−0.97	3.94	24.59	−0.25	.808
Condition (DT)	−0.09	1.09	27.98	−0.09	.931
Speaking task (E)	−0.43	0.65	38.35	−0.66	.513
Sex	1.55	3.73	23.00	0.42	.681
Group × Condition	1.19	1.51	27.98	0.79	.435
Group × Speaking Task	−1.10	0.90	38.35	−1.22	.231
Condition × Speaking Task	−0.26	0.68	23.00	−0.38	.711
Group × Speaking Task × Condition	0.64	0.95	23.00	0.67	.507
F0SD (semitones)					
Intercept	3.66	0.42	25.20	8.80	< .0001**
Group (PD)	−0.69	0.61	25.59	−1.14	.265
Condition (DT)	−0.01	0.15	46.00	−0.04	.969
Speaking task (E)	0.15	0.29	30.01	0.53	.603
Sex	0.37	0.56	23.00	0.67	.510
Group × Condition	0.14	0.20	46.00	0.70	.486
Group × Speaking Task	−0.28	0.40	30.01	−0.70	.491
Condition × Speaking Task	0.13	0.21	46.00	0.64	.526
Group × Speaking Task × Condition	−0.49	0.29	46.00	−1.70	.096

Note. The intercept is mapped to the control group in the single-task condition. AAVS = articulatory–acoustic vowel space; PD = Parkinson disease; DT = dual task; E = extemporaneous; F0SD = standard deviation of fundamental frequency.

*$p < .05$. **$p < .001$.

compared to healthy controls (e.g., Tucha et al., 2006; van Gemmert, Adler, & Stelmach, 2003; van Gemmert, Teulings, Contreras-Vidal, & Stelmach, 1999). For example, Tucha et al. (2006) found that the distance of the ascending and descending strokes of handwriting movements were significantly shorter for participants with PD than controls, regardless of medication state. In a study of different handwriting patterns, Teulings et al. (1997) found that motor control differences between participants with PD and controls occurred primarily for handwriting movements that required coordination of finger and wrist movements. The current study found that peak movement frequency was lower on average for individuals in the PD group compared to controls. Other authors have reported similar findings, observing reduced speed of handwriting gestures in individuals with PD compared to controls (e.g., Teulings et al., 1997; Teulings

& Stelmach, 1991; Tucha et al., 2006). Therefore, baseline differences in upper extremity (i.e., manual) motor control were observed between individuals with PD and controls. These differences likely reflect the underlying motor impairment because they align with prior findings reported for similar tasks.

The current study also observed significant dual-task effects on manual task kinematics for individuals with PD that were not observed for individuals in the control group. Specifically, participants with PD exhibited significant increases in the variability of mean radius from the single- to dual-task conditions when performing the manual task with both the reading and extemporaneous speech tasks. Participants in the older adult control group only exhibited an increase in the mean radius variation when the manual task was performed with the extemporaneous task, compared to the reading task. However, visual comparison of the mean variability in radius for controls in the dual-task extemporaneous condition was comparable to that in the single-task condition (see Figure 3). These data suggest that participants with PD exhibited dual-task interference regardless of the speaking task, whereas controls exhibited only slight dual-task interference when the manual task was performed with the extemporaneous task compared to the reading task, but not more than in the single-task condition. van Gemmert et al. (1998) reported a similar finding when examining the effect of numeric recitation and mental manipulation on handwriting movements. Participants with PD exhibited an increase in movement duration and normalized jerk when handwriting movements were performed with concurrent numerical repetition and mental manipulation (i.e., subtraction). Control participants exhibited similar changes when the handwriting task was performed with the mental manipulation task, but not during numeric repetition (van Gemmert et al., 1998). As in the study by van Gemmert et al. (1998), participants with PD in the current examination exhibited significant dual-task interference, regardless of the speaking task, suggesting manual motor control in individuals with PD is more vulnerable to dual-task interference than for neurologically healthy controls.

Speech Task Performance

Statistically significant differences between speakers with PD and controls were observed for some of the acoustic measures. For example, the PD group exhibited a significantly smaller AAVS than controls regardless of speaking task or condition, suggesting that speakers with PD exhibited a smaller working vowel space than controls. Prior work suggests that speakers with PD often exhibit smaller vowel space metrics than controls (e.g., Hsu et al., 2017; Tjaden, Lam, & Wilding, 2013; Whitfield & Goberman, 2014). Authors examining measures of working vowel space have reported sex-related differences in the AAVS, likely due to differences in vocal tract size between males and females (Whitfield et al., 2018; Whitfield & Goberman, 2017a). Although the male speakers in the current study did exhibit smaller AAVS values on average than the female speakers, this contrast was not statistically significant. The PD group was composed of a larger proportion of male participants than the control group. This imbalance in the male-to-female ratio between groups may have contributed to the observed effect of group in the current study.

Additionally, speakers with PD also exhibited pause durations that were 72% longer than those of control speakers in the extemporaneous task. Significantly longer pause durations, greater percent pause time, and a greater number of pauses per second in the speech of individuals with PD compared to controls have been reported in other studies of extemporaneous speech (Goberman et al., 2005; Rusz, Cmejla, Ruzickova, & Ruzicka, 2011; Tjaden & Wilding, 2011). Note that the current study defined pause as a silent interval in speech that lasted 150 ms or longer and was not associated with a stop gap. As such, pauses examined in the current study captured longer silent intervals in speech associated with prosodic, linguistic, and cognitive processes rather than short articulatory events such as a between- or within-word stop gap.

No differences were observed between speakers with PD and controls for speech intensity. On average, speakers with PD exhibited a slightly lower speech intensity than controls, though this difference was not statistically significant. Though several studies document that speakers with PD typically exhibit a reduction in vocal intensity that is, on average, 2–5 dB (e.g., Fox & Ramig, 1997; Ho, Bradshaw, Iansek, & Alfredson, 1999; Ho et al., 2002), others have reported comparable speech intensity values between speakers with PD and controls in controlled environments (e.g., Lam & Tjaden, 2016). Although there are a number of potential explanations for this finding, data from other work suggest that speakers with PD exhibit greater speech intensity when performing experimental speech tasks in controlled lab settings compared to tasks performed in contexts that place a greater demand for speech intensity regulation (e.g., S. G. Adams et al., 2010; Bunton & Keintz, 2008; Clark, Adams, Dykstra, Moodie, & Jog, 2014; Dykstra, Adams, & Jog, 2012; Ho et al., 1999; McCaig et al., 2016). Bunton and Keintz (2008) found that speakers with PD exhibited greater speech intensity when performing prompted reading and monologue tasks wearing a head-mounted microphone than during spontaneous speech samples that were elicited without the speaker's knowledge. Other work demonstrates that speakers with PD exhibit less robust increases in speech intensity levels than controls when speaking in various noise levels and imitating speech intensities (e.g., S. Adams et al., 2006; Ho et al., 1999). Data from this work suggest that speech intensity deficits associated with PD may be more prevalent in conversational contexts than in the laboratory setting (S. G. Adams et al., 2010; Bunton & Keintz, 2008; Clark et al., 2014; Dykstra et al., 2012; Ho et al., 1999; McCaig et al., 2016). Therefore, the current finding may be explained by a combination of these factors, namely, that the speech samples were collected under ideal laboratory conditions and with specific knowledge of the participants. This hypothesis may also help to explain why no acoustic differences were observed between speakers with PD and controls for the single-task readings.

Concurrent Task Performance

A primary aim of the current investigation was to examine the effect of a simple manual task on connected speech acoustics in speakers with and without PD. In the current investigation, no dual-task effects were observed for either group when the oscillatory manual task was performed with paragraph reading. Control participants did not exhibit a change in any speech acoustic measure between the single- and dual-task conditions for either speaking task. For the current investigation, little to no dual-task effects were expected in the control group for the speech production tasks because the secondary task was purposefully chosen to be a simple, repetitive manual task that could be performed in a relatively autonomous fashion, and it required little to no attentional resources (e.g., Saltuklaroglu et al., 2009). Prior studies of healthy talkers suggest that secondary tasks that place a higher demand on attentional resources have a greater effect on speech production than lower demand motor tasks (e.g., S. G. Adams et al., 2010; Dromey & Bates, 2005; Dromey & Benson, 2003; Dromey & Shim, 2008; Kemper et al., 2003; Kemper, Herman, & Nartowicz, 2005). For example, changes in speech rate and intensity have been observed in control speakers when performing a visuomotor task concurrently with extemporaneous speech, suggesting that higher demand motor tasks that contain a visual component affect speech motor control (S. G. Adams et al., 2010; Kemper et al., 2003, 2005). Because no systematic changes in speech acoustics were observed in control speakers in the current investigation, it can be inferred that the addition of a low-demand motoric task did not interfere with speech production processes associated with performance of either speech task in neurologically healthy older adults.

Similar to the control group, speech acoustics of the reading task were not affected by concurrent performance of the manual task in the PD group. These data may suggest that, like controls, the combined demands of reading and manual task performance were not sufficient to disrupt speech production processes in this speaker group. Speakers in the PD group, however, exhibited a significant reduction in pause duration between the single- and dual-task conditions for the extemporaneous task, suggesting that the combined demands of extemporaneous speech and upper extremity movement affected performance of both tasks. Whereas these findings generally align with prior reports that have observed changes in speech acoustics when speakers with PD perform two tasks concurrently (e.g., S. G. Adams et al., 2010; Bunton & Keintz, 2008; Dromey et al., 2010; Ho et al., 2002), other authors have reported dual-task effects on speech acoustics that were not observed in the current study.

Prior work has reported that speakers with PD may exhibit change in speaking rate, variability of speaking F0, speech intensity, and formant frequency trajectories between single-task, speech-only conditions and when performing a speech and secondary task concurrently (S. G. Adams et al., 2010; Bunton & Keintz, 2008; Dromey et al., 2010; Ho et al., 2002). However, it is possible that the nature and demands of the secondary task differentially impact speech production during concurrent task performance. For example, studies examining tasks that require greater attentional load or tax the postural system have observed significant effects on speech production for speakers with PD (e.g., S. G. Adams et al., 2010; Dromey et al., 2010; Ho et al., 2002).

It is possible that the nature and demands of the secondary task differentially impact speech intensity under dual-task conditions in speakers with and without PD. S. G. Adams et al. (2010) reported that, whereas controls exhibited a decrease in conversational speech intensity when performing a visuomotor task (i.e., a visuomotor tracking task controlled using a hand bulb), speakers with PD exhibited a significant increase in speech intensity from single- to dual-task performance. Another study by McCaig et al. (2016) reported that speakers with PD exhibited increases in conversational speech intensity with concurrent walking compared to standing and that faster walking speeds led to greater speech intensities than slower speeds. Conversely, Ho et al. observed no changes in conversational speech intensity when individuals with PD performed a concurrent visuomotor task, though significantly greater decrements in speech intensity were observed over the course of the speaking task when the secondary task was performed while counting aloud (Ho et al., 2002). The current results for speech intensity align with those reported by Ho et al. (2002), as no significant changes in speech intensity were observed between single- and dual-task conditions.

Changes in working vowel space area (e.g., the AAVS) were not observed in the current study between the single- and dual-task conditions for speakers in the PD group. In contrast, Dromey et al. (2010) reported a significant reduction in the extent and slope of diphthong formant trajectories when speakers with PD simultaneously performed a sentence repetition and a postural stability task, suggesting that dual-task performance affects spectral measures that indirectly reflect speech articulation. Segment-level formant trajectory metrics were not examined in the current investigation, making direct comparisons to data from Dromey et al. difficult. However, random effects suggested that there was significant variation between the condition-related change in the AAVS and articulation rate between participants, indicating that there was individual variation in the pattern of the dual-task effect. For the AAVS, the mean absolute percent change was slightly larger for the PD group (11%) compared to the control group (8%). However, the directionality of the change in vowel space also varied across speakers, with some participants with PD exhibiting a decrease in vowel space and others exhibiting an increase between the single- to dual-task conditions. A prior study examining dual-task performance in speakers with PD also observed individual differences in the pattern of dual-task effects in speakers with PD (Whitfield & Goberman, 2017b). In that study, Whitfield and Goberman (2017b) found that, although most speakers with PD exhibited an increase in speaking duration (i.e., a slowing of speech rate) during concurrent task performance, a small subset of participants exhibited a slight increase in rate from the single- to dual-task conditions. Future work should examine associations between the magnitude of dual-task effects and other variables associated with cognitive and motor status in speakers with PD to better explain these patterns.

Other authors have reported that concurrent task performance significantly affects the speaking rate of individuals with PD (Bunton & Keintz, 2008; Dromey et al., 2010; Ho et al., 2002). Ho et al. (2002) observed a reduction in conversational speaking rate in speakers with PD, but not controls, when an extemporaneous speech task was performed with a concurrent visuomotor task. Whitfield and Goberman (2017b) found that most speakers with PD exhibited an increase in speaking duration (i.e., a slowing of speech rate) when a recently learned nonword sequence was performed with an attention-demanding visuomotor pursuit task. Conversely, Bunton and Keintz (2008) observed an increase in speech rate when four speakers with PD performed a simple manual task (i.e., turning a nut on a bolt) compared to speaking alone. Although changes in articulation rate were not observed between conditions in the current study, the reduction in pause duration observed for speakers in the PD group would have resulted in an increased global speaking rate. In light of the current and prior findings, the nature of the secondary task may mediate the effect of concurrent task performance on speaking rate, with more attention-demanding tasks resulting in a slower speech rate and simpler motor interference tasks resulting in an increase in speaking rate.

There are several potential hypotheses that explain the decrease in pause duration from the single- to dual-task conditions for speakers with PD. First, it is possible that the reduction in pause duration from the single- to dual-task conditions observed in speakers in the PD group marked an improvement in prosodic timing, as speakers with PD exhibited significantly longer pause durations than controls in the single-task condition. The reduction in pause duration from the single- to dual-task conditions, however, likely resulted in an overall increase in speaking rate. A faster-than-normal speaking rate and a reduction in proportional pause timing are commonly reported features of hypokinetic dysarthria (e.g., Huber & Darling, 2011; Metter & Hanson, 1986). Additionally, other work suggests that a slower speaking rate, longer pause durations, and larger vowel space areas are acoustic characteristics of clearly produced speech (e.g., Lam & Tjaden, 2013; Picheny, Durlach, & Braida, 1986; Whitfield & Goberman, 2017a). In the current study, speakers with PD exhibited an increase in speaking rate associated with a reduction in pause durations from the single- to dual-task conditions. Future work should explore the impact of secondary task performance on perceptual measures of speech to determine the effect of this reduction in pause on speech clarity and speech symptom severity.

The pattern of results does not support the notion that speakers with PD exhibited a significant change in speech articulation from the single- to dual-task conditions, as there were no robust changes in the AAVS or articulation rate. Rather, the dual-task effects on speech rate associated with a reduction in pause duration likely reflect changes in another dimension, such as prosody or linguistic processing. For example, it is possible that the reduction in mean pause duration from the single- to dual-task conditions observed for speakers in the PD group reflects a reduction in linguistic planning or processing during the extemporaneous speech task. Prior work by Kemper et al. suggests that, under attention-demanding dual-task conditions, healthy older adults preserve grammatical complexity and information content, while sacrificing speech rate (e.g., Kemper et al., 2003, 2005, 2011, 2009). A study by Kemper et al. (2005) found that neurologically healthy older adults exhibited an increase in speech rate and normal disfluencies when an extemporaneous speech task was performed with an attention-demanding visuomotor task. Though dual-task performance was associated with changes in rate and fluency, changes in measures of grammatical complexity and information content were not affected by dual-task performance. The authors suggest that, by sacrificing speech rate and fluency, as well as secondary task performance, healthy older adults are able to rely upon a cognitive reserve capacity to preserve the complexity and content under dual-task conditions (Kemper et al., 2003, 2005).

In light of the work by Kemper et al. (2005), these data may suggest that speakers with PD in the current study sacrificed linguistic complexity or content (e.g., lexical retrieval, marking of grammatical boundaries, semantic planning) when performing the extemporaneous speech task with the concurrent manual task. Coupled with dual-task costs observed for the manual task, these findings might suggest that the combined linguistic, speech motor, and manual motor demands associated with concurrent performance exceed the attentional capacity required for successful dual-task performance for the PD group. Additionally, it is possible that subtle cognitive impairments associated with PD may have led to differences in attentional capacity between the groups, effectively increasing the attentional load of concurrent task performance for the PD group. Because no data on linguistic complexity or content were measured, these interpretations are merely hypothetical and should be taken with great caution. Nonetheless, the current results suggest that speakers with PD exhibit bidirectional dual-task effects characterized by changes in both the extemporaneous speech (i.e., an increase in speech rate associated with a reduction in mean pause duration) and manual (i.e., increased movement variability) tasks when the tasks were performed concurrently.

Limitations and Future Directions

The current investigation has some important limitations that should be addressed. First, an order effect is inherent to all repeated-measures designs. It is therefore possible that the repeated readings of the Rainbow and John Passages led to improved performance in the dual-task condition. For example, a prior study by Whitfield, Delong, Goberman, and Blomgren (2018) observed a significant reduction in stuttering-like disfluencies with successive readings of the Rainbow Passage. The prompts used during the extemporaneous tasks were randomized between conditions and were thus not repeated between the single- and dual-task conditions. Although prior work suggest that the prompts used in the current study elicit extemporaneous speech that is comparable in linguistic structure (e.g., Kemper et al., 2005, 2009), it is possible that there were differences in speech articulation and prosody. Randomization of prompt order between participants was completed to control for potential order effects and differences between the prompts that may have influenced speech production.

A few inherent limitations associated with the current sample should be mentioned. First, the number of speakers with PD examined in the current study was relatively small. Additionally, disease duration spanned a wide range, which increased between-participant variability. For example, random effects revealed significant variation between participants in the dual-task cost observed for the acoustic measures of articulation, specifically the AAVS and articulation rate. Future work should examine the extent to which dual-task changes in articulatory parameters relate to baseline measures of motor, cognitive, and affective status, as individual participant characteristics may better explain changes in articulation associated with dual-task performance. Also, a number of cognitive and affective variables not included in the statistical models are known to affect baseline motor performance (e.g., Caligiuri & Ellwanger, 2000; Sabbe, Hulstijn, van Hoof, Tuynman-Qua, & Zitman, 1999). Thus, further exploration into the interactions between other measures of affective, cognitive, and motor control and dual-task performance in individuals with PD is warranted. Finally, differences in the male-to-female ratio between groups should also be acknowledged as an inherent weakness of the current sample, as several acoustic measures of speech production such as formant space metrics differ between male and female speakers. However, no statistically significant acoustic differences between male and female participants were observed in the current study. Nonetheless, considering these limitations, further replication of these findings in a larger sample of speakers with PD is necessary before the current results can be generalized to a larger population of speakers with PD.

A strength of the current study was that dual-task performance was characterized using several measures of speech articulation (including utterance-level, working vowel space estimates) and speech prosody. However, dual-task performance was assessed using measures that were averaged over an entire speaking task, neglecting local measures of speech production that may have provided a more nuanced perspective of the dual-task costs. Prior work suggests that speakers with PD may exhibit subtle changes in speech production over the course of a speaking task (e.g., Ho et al., 2002; Kuo & Tjaden, 2016; Skodda & Schlegel, 2008). Additionally, it is possible that participants alternated task priority over the course of an experimental trial in the dual-task condition. In light of these prior findings and considerations, future investigations should consider quantifying the tradeoffs in dual-task performance and evaluate local changes over the course of the task. Additionally, findings from the current investigation may suggest that changes in speech production associated with concurrent task performance in speakers with PD may be prosodic, rather than articulatory, in nature. Future work should explore changes in linguistic measures, such as grammatical complexity and informational content between the single- and dual-task conditions to further delineate the dual-task costs observed in extemporaneous speech. Finally, the aim of the current investigation was to quantify baseline interference associated with a low-demand secondary task that required repetitive manual movement. Therefore, only one secondary motor task was examined. Future studies should consider delineating the effects of a hierarchy of tasks that vary in attentional load to determine the extent to which dual-task interference is modulated by the combined demands of the dual-task condition.

Acknowledgments

Portions of this work were funded by grants from the Vice President for Research and Economic Engagement and the Center for Undergraduate Research and Scholarship at Bowling Green State University. The first author received an internal grant that supported the completion of this project. We would like to acknowledge Michaela Natal and Anna Gravelin for assisting with data collection efforts and Michaela Natal, Josie Clark, and Abbie Bates for assistance with data analysis.

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