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Effects of a Concurrent Working Memory Task on Speech Acoustics in Parkinson's Disease

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ABSTRACT

Purpose: The purpose of this study was to determine the effect of a concurrent working memory task on acoustic measures of speech in individuals with Parkinson's disease (PD).
Method: Individuals with PD and age- and sex-matched controls performed a speaking task with and without a Stroop-like concurrent working memory task. Cepstral peak prominence, low-to-high spectral energy ratio, fundamental frequency (f_o) standard deviation, articulation rate, pause duration, articulatory–acoustic vowel space, relative f_o, mean voice onset time (VOT), and VOT variability were calculated for each condition. Mixed-model analyses of variance were performed to determine the effects of group, condition (presence of the concurrent working memory task), and their interaction on the acoustic measures.
Results: All measures except for VOT variability, mean pause duration, and relative f_o offset differed between people with and without PD. Cepstral peak prominence, articulation rate, and relative f_o offset differed as a function of condition. However, no measures indicated disparate effects of condition as a function of group.
Conclusion: Although differentially impactful on limb motor function in PD, here a concurrent working memory task was not found to be differentially disruptive to speech acoustics in PD.
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Parkinson's disease (PD) is a neurological disorder that results in both motor and nonmotor symptoms (Chen et al., 2020). Clinical diagnosis typically focuses on specific motor features of the disease, such as tremor and impairments of gait (Koller, 1992; Rajput et al., 1991); however, these features often appear years following the initial onset of the disease (Borsche et al., 2019; Ruiz-Lopez et al., 2019). In contrast, speech production, which relies on both motor and nonmotor processes, is often affected prior to the diagnosis of PD (Kotz et al., 2009). In fact, over 90% of people with PD (PwPD) eventually develop hypokinetic dysarthria (Logemann et al., 1978; Müller et al., 2001), which includes impairments in voice quality, prosody, articulatory clarity, and speech coordination (Darley et al., 1969; Duffy, 1995). The severity of hypokinetic dysarthria may be exacerbated by other nonmotor symptoms in PD, including cognition (Tjaden, 2008).

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Impaired cognition is common in PwPD (Aarsland et al., 2003, 2017; Braak et al., 2005; Muslimovic et al., 2009). Cognitive impairments have often been demonstrated by manipulating cognitive load using dual tasking, in which a secondary task is performed simultaneously with a speech production task (O'Shea et al., 2002; Raffegeau et al., 2019; Whitfield et al., 2019). The most comprehensive examination of the effects of increased cognitive load on speech production in PwPD used a dual-tasking paradigm with concurrent motor and speech tasks in 12 PwPD and 11 individuals without PD (Whitfield et al., 2019). The dual-tasking paradigm was used in Whitfield et al. (2019), in which the secondary task introduced a concurrent motor load, consisting of participants drawing continuous circles while producing speech. This secondary task added complexity, but its cognitive difficulty was not particularly high. Researchers found little-to-no effect of this increased cognitive load in either group on measures of vowel space area, articulation rate, or fundamental frequency (f_o) variability (Whitfield et al., 2019). These results, however, conflict with the majority of previous studies examining the effects of cognitive load on speech production in other populations, which have typically incorporated cognitive loads with varying demands on working memory (MacLeod, 1991; MacLeod & MacDonald, 2000; MacPherson, 2019). During these working memory tasks, individuals performed a speech task, involving the Stroop task, or Stroop-like tasks. In these tasks, the additional cognitive load is time-shared with speech production, which may result in an integrated response (i.e., the end response is a verbal output produced by the speech system). Although these tasks involve shared cognitive resources, the addition of the working memory task presents a substantial change to the cognitive load of the combined tasks.

It is possible that the conflict between the findings in PwPD and individuals with typical speech is a result of methodological differences. Specifically, a concurrent working memory demand, like that used in the studies of those with typical speech, may exacerbate aspects of dysarthria in PwPD more so than a concurrent motor task. If so, this may have ramifications for early identification of PwPD: Concurrent demands on working memory could strain the speech motor control system, revealing subclinical changes in speech parameters that are consistent with dysarthria (changes in voice quality, prosody, articulatory clarity, and speech coordination). Alternatively, if an additional cognitive challenge does not result in more dysarthric features of speech, this may imply that dysarthric features are related to more peripheral symptoms of PD (e.g., stiffness) than to higher-order characteristics of speech motor control, or perhaps the task at hand may not be difficult enough to produce differences in the characteristics of speech production.

Reduced cognition significantly affects symptoms related to limb motor control (Christofoletti et al., 2016; Paul et al., 2013), so a concurrent cognitive load may reveal subclinical changes in dysarthria. Although the commonly used concurrent working memory task (Stroop task) is not common in everyday communication, more common cognitive challenges during communication (e.g., providing directions for tasks, navigating difficult conversations, etc.) are difficult to implement in a controlled fashion. Thus, the current study sought to examine acoustic features of hypokinetic dysarthria in PwPD during a Stroop-based simultaneous cognitive load.

Voice quality is often impaired in PwPD, with reports of rough, breathy, and/or strained voices (Skodda, 2011; Skodda et al., 2013). To acoustically evaluate changes in voice quality associated with roughness and breathiness during running speech, investigators can observe cepstral peak prominence (CPP) and low-to-high spectral energy ratio (L/H ratio) values. In neurologically typical speakers, cognitive stress has been shown to increase CPP and lower the L/H ratio, likely due to the use of a more pressed voice (MacPherson et al., 2017). However, previous studies without a simultaneous cognitive task found that speakers with severe dysarthria had lower CPP and lower L/H ratios compared to those with mild dysarthria (Heman-Ackah et al., 2002; E. A. Peterson et al., 2013), consistent with weaker and breathier voice production in severe dysarthria. Thus, if a simultaneous working memory task exacerbates symptoms of dysarthria in PwPD, they may have qualitatively different changes in voice quality under the working memory task than do people without PD.

With respect to changes related to vocal strain, relative fundamental frequency (RFF) can be used as an acoustic correlate. RFF is an estimate of the f_o of individual voicing cycles during transitions between vowels and voiceless consonants (Stepp, 2013). PwPD present with lower RFF compared to neurologically typical speakers, which may be indicative of increased laryngeal tension (Goberman & Blomgren, 2008; Stepp, 2013; Vojtech & Stepp, 2022). Increased laryngeal muscle tension in PwPD has been shown to correlate with increased severity of dysarthria, typically seen as a strained or pressed voice quality (Cernak et al., 2017; Oates, 2009). In neurologically typical speakers, a simultaneous working memory task has been associated with lower RFF (Dahl & Stepp, 2021). RFF has not yet been examined using a working memory task in PwPD, but exacerbation of dysarthria symptoms under the effect of the task would likely result in increased vocal strain and lower RFF values, which is consistent with the response seen in speakers without PD. Thus, preexisting symptoms of dysarthria may sum in PwPD, causing even larger decreases in RFF during a simultaneous working memory task than those seen in individuals without PD.

Impaired prosody in PwPD is often characterized by decreased intonational variation (Skodda, 2011; Skodda et al., 2011). To measure intonation, typically f_o variability across an utterance is calculated (Bowen et al., 2013; Bunton & Keintz, 2008; Watson & Schlauch, 2008). This f_o standard deviation (*SD*) is often lower in PwPD compared to neurologically typical speakers (Bowen et al., 2013; Skodda, 2011), which may drive listener perceptions of monotonicity of speech in this population (Canter, 1963; Watson & Schlauch, 2008). Researchers have found cognitive stress to be associated with increased f_o *SD* in neurologically typical speakers (Boyer et al., 2018; Lively et al., 1993; Mendoza & Carballo, 1998; Whitfield et al., 2019); however, f_o *SD* has not been examined using a working memory task in PwPD. If dysarthria symptoms were exacerbated under the effect of a working memory task, this would likely result in reduced f_o *SD* in PwPD, in contrast to increased f_o *SD* previously documented in individuals without PD (Boyer et al., 2018; Lively et al., 1993; Mendoza & Carballo, 1998).

Another aspect of prosody is speech timing, which is known to be affected by PD (Skodda, 2011; Skodda et al., 2011; Tjaden & Wilding, 2011; Whitfield et al., 2019). Articulation rate and pause duration, together, may give insight into the effect PD has on overall speech rate (Tjaden & Wilding, 2011). Increased cognitive load is associated with decreased articulation rate and increased pause duration in neurologically typical speakers (Khawaja et al., 2008). Compared with neurologically typical individuals, previous studies have found contradictory results with respect to pause duration and articulation rate in PwPD (Skodda & Schlegel, 2008; Tjaden & Wilding, 2011). Thus, if exacerbation of the symptoms of dysarthria does not result in consistent changes in speech timing, one might anticipate that under a working memory task, PwPD will respond similarly to individuals without PD, with decreased articulation rate and longer pause durations.

PwPD often present with reduced articulatory clarity, typified by a reduced range of motion of speech articulators (Pawlukowska et al., 2015; Rusz et al., 2013; Tjaden et al., 2013; Whitfield & Goberman, 2014). Vowel space area is one way to quantify this imprecise articulation. Specifically, the articulatory acoustic vowel space (AAVS) captures subtle articulation differences in PwPD, otherwise undetectable when using traditional vowel space area methods (Whitfield & Goberman, 2014). AAVS incorporates all voiced sounds during running speech, which makes it more ecologically valid compared to traditional vowel space area methods (Whitfield & Goberman, 2017). Cognitive stress is associated with decreased vowel space area in neurologically typical speakers (Hasegawa-Johnson et al., 2003; Tjaden et al., 2013), and previous studies found reduced AAVS in PwPD compared to neurologically typical speakers (Bang et al., 2013; Whitfield & Goberman, 2014), although AAVS has not been examined during a working memory task in PwPD. Thus, increased symptoms of dysarthria during a simultaneous working memory task are likely to result in lower AAVS values in PwPD.

Finally, PwPD often have difficulty coordinating speech articulators. One feature of speech that is particularly reliant on coordination across articulators is voice onset time (VOT). VOT, an acoustic measure reflecting the duration of the period between the release of a plosive (stop) and the onset of voicing, is used to evaluate the presence of voicing during the production of stop plosives (Lisker & Abramson, 1964). VOT is reliant on an individual's ability to coordinate laryngeal movements and oral release (Fischer & Goberman, 2010; Forrest et al., 1989). Reduced inter-articulator coordination could result in shorter or longer VOTs relative to typical speakers. However, previous work found shorter mean VOT values in PwPD when compared to neurologically typical controls (Darley et al., 1969; Morris, 1989; Weismer, 1984), perhaps due to decreasing the range of motion of speech articulators (Weismer, 1984). Although no studies have directly examined the trial-to-trial variability of VOT in PD, PwPD have been shown to have increased trial-to-trial variability in the coordination of their lips and jaw, regardless of their sound pressure (Darling & Huber, 2011). Further, although findings suggest variability in the directionality of differences in this population, research suggests that PwPD may exhibit a greater degree of overlap in the VOT distribution of voiced and voiceless stops (Flint et al., 1992; Forrest et al., 1989). These findings indicate an overall loss of speech coordination (Forrest et al., 1989; Richardson et al., 2014; Weismer, 1984). Researchers have found contrasting results on mean VOT under cognitive stress in neurologically typical speakers (Casini et al., 2009; Chiu et al., 2020). Neither mean VOT nor VOT variability has been examined during a working memory task in PwPD. If symptoms of dysarthria are increased during a concurrent working memory task, we expect to find reduced mean VOT values and increased VOT variability in PwPD in this condition, reflecting reduced inter-articulator coordination.

The purpose of this study was to understand the effects of a concurrent working memory task on voice quality, prosody, articulatory clarity, and speech coordination in PwPD, with the overarching hypothesis that the concurrent working memory task would exacerbate their preexisting or subclinical symptoms of dysarthria. Using a speech task with two conditions allowed us to analyze acoustic measures during typical speech production and under the effect of a working memory task. We hypothesized that, during the working memory task, PwPD would show differences consistent with more severe hypokinetic dysarthria and that these differences would be larger than those seen in individuals with typical speech.

Method

Participants

Twenty-seven PwPD and 27 individuals with typical speech (henceforth referred to as controls) participated in this study. All participants provided written informed consent in accordance with the Boston University Institutional Review Board. No controls reported a history of any speech, language, hearing, or neurological disorder. Participants with PD were 12 females and 15 males (M = 61.2 years, SD = 7.4 years, range: 46–74 years of age).[1] Controls were sex- and age-matched within 4 years (M = 61.2 years, SD = 7.5 years, range: 46–76 years of age). Time since PD diagnosis ranged from 1 to 25 years (M = 7.2 years, SD = 5.6 years). Each PwPD was evaluated by a trained technician certified to perform the Movement Disorder Society's revision of part III of the United Parkinson's Disease Rating Scale (MDS-UPDRS), which assesses motor signs of PD (Goetz et al., 2008). MDS-UPDRS III scores ranged from 15 to 49 (M = 47.7, SD = 18.4), representing mild to moderate levels of motor impairment.

The severity of dysarthria of each speaker was characterized by a blinded, certified speech-language pathologist using an equal-appearing interval scale from 0 to 4. Each category was labeled as follows: 0 = *typical speech*, 1 = *mild dysarthria*, 2 = *moderate dysarthria*, 3 = *severe dysarthria*, and 4 = *profound dysarthria*. Ratings were based on two sentences from the data set stimuli for each participant with PD; 10% of speech samples were repeated to assess intrarater reliability. Dysarthria severity ranged from 0 to 3 in PwPD (*Mdn* = 1, *interquartile range* = 0–2), representing a range from typical speech to severe levels of dysarthria. Intrarater reliability was evaluated using level of agreement: 83% of ratings were in perfect agreement, whereas the remaining 17% of ratings differed within one category (e.g., 1 vs. 2). A second blinded, certified speech-language pathologist rated 10% of participants to allow computation of interrater reliability. Of these, 67% of ratings were in perfect agreement with the original rater, whereas the 33% of ratings that differed were within one category (e.g., 1 vs. 2).

The perceptual quality of each speaker's voice was assessed by a blinded, voice-specializing certified speech-language pathologist who completed the Consensus Auditory-Perceptual Evaluation of Voice (CAPE-V; Kempster et al., 2009). Two sentences from the data set for each participant with PD were evaluated; CAPE-V ratings were completed using a visual analog scale ranging from 0 to 100, with anchors for mild at 10, moderate at 35, and severe at 72. Overall severity ratings in PwPD ranged from 2.56 to 32.76, representing a range of no dysphonia to mild levels of dysphonia. Overall severity ratings for participants with PD are shown in Table 1. All CAPE-V rating parameters (breathiness, roughness, strain) similarly ranged from no dysphonia to mild dysphonia.

Cognition, color-blindness, and hearing were assessed in all participants. Participants completed the Montreal Cognitive Assessment (MoCA), which is scored out of 30 points, with typical cognition being scored as greater than or equal to 26 (Nasreddine et al., 2005). To ensure that all participants were able to provide informed consent, individuals who scored below 22 points on the MoCA were excluded from participating (Karlawish et al., 2013). Of the participants with PD, the MoCA scores ranged from 22 to 30 (M = 27.0, SD = 2.2 points), whereas MoCA scores for the control participants ranged from 24 to 30 (M = 27.8, SD = 1.6). Full demographics for participants with PD are shown in Table 1. All participants passed a color-blindness test (Ishihara, 1973) and pulsed pure-tone hearing screening at a threshold of 25 dB HL at octaves from 125 to 1000 Hz and 40 dB HL at 2000 and 4000 Hz (Schow, 1991).

Procedure

Acoustic recordings of each participant were obtained using a head-mounted microphone (Shure omnidirectional MX153 or Shure SM35 XLR) placed 45° from the midline and 7 cm from the lips. These were recorded with 16-bit resolution and at a sampling rate of 44.1 kHz in a sound-treated room at Boston University.

Participants were presented with a list of 12 sentences, which contained text in black ink, followed by four color names printed in colored ink, and followed by additional text in black ink (e.g., "Later Marie painted red, blue, pink, and green for two paintings in a row"; see the Appendix for a full list of sentences). The first six sentences were congruent: The ink color matched the name of the color (e.g., "purple" was printed in purple ink). The following six sentences were incongruent: The ink color did not match the name of the color (e.g., "purple" was printed in green ink). Participants were instructed to read the sentences aloud and name the color of the ink for the color words embedded in the sentences. Compared to the congruent sentences, the incongruent sentences were designed to increase working memory demands (Kane & Engle, 2003; Pan et al., 2019). Congruent sentences were immediately followed by incongruent sentences. This set order of sentences was chosen to eliminate the risk of any response induced during the incongruent sentences from carrying over into the congruent sentences (B. S. Peterson et al., 1999; Taylor et al., 1994).

To note, members of both the PD and control groups had difficulty discriminating between certain ink colors (e.g., saying "pink" instead of "red"), noted as color discrimination errors. Other errors included failure

[1]Information about gender was not recorded for all speakers, so only sex is reported here.

Table 1. Age, sex, MDS-UPDRS PIII motor score (< 33 indicates mild impairment, and > 59 indicates severe impairment), dysarthria ratings for overall severity of dysarthria (0 = *typical speech* and 4 = *profound dysarthria*), MoCA scores (out of 30), and OS ratings from the CAPE-V for all participants with Parkinson's disease.

ID	Age	Sex	MDS-UPDRS PIII	Dysarthria rating	MoCA	OS CAPE-V
PD19	70	F	77	2	22	8.55
PD25	68	M	66	1	23	20.79
PD14	54	F	36	0	24	5.84
PD27	52	F	22	1	24	5.41
PD2	55	M	49	2	24	9.97
PD12	60	M	54	3	24	17.65
PD3	62	M	50	2	25	4.56
PD7	68	M	48	3	25	29.06
PD21	67	F	50	1	26	8.83
PD23	61	F	34	0	27	3.13
PD4	74	F	94	1	27	24.59
PD18	46	M	75	1	27	18.09
PD1	50	M	17	0	28	4.99
PD17	66	F	45	0	28	5.98
PD5	69	F	47	1	28	11.00
PD8	52	M	33	1	28	8.83
PD22	55	M	26	1	28	25.64
PD10	65	M	47	2	28	26.78
PD24	62	M	47	2	28	31.33
PD6	65	F	15	0	29	2.56
PD11	64	F	35	0	29	5.69
PD16	73	M	63	0	29	5.13
PD13	49	M	47	1	29	3.00
PD15	63	F	38	1	29	5.69
PD20	67	M	76	2	29	14.53
PD26	59	F	53	0	30	6.84
PD9	57	M	43	1	30	32.76

Note. MDS-UPDRS PIII = Movement Disorder Society Unified Parkinson's Disease Rating Scale Part III; MoCA = Montreal Cognitive Assessment; OS = overall severity; CAPE-V = Consensus Auditory-Perceptual Evaluation of Voice; F = female; M = male.

to respond to the task, in which participants responded with the written text color rather than stating the ink color. In total, 84% of the total errors were color discrimination errors. Of the color discrimination errors, 45% were made by controls and 55% were made by PwPD. A chi-square test of independence was performed to examine the relation between group (PwPD and controls) and the type of error. There was no significant association between group and error type, $\chi^2(1, N = 228) = 0.37$, $p = .54$.

The difference in speech rate between congruent and incongruent sentences was measured. Sentences were not included in analyses if they had a difference greater than 5.5 s between congruent and incongruent, resulting in 13 excluded sentences in PwPD (4% total) and seven excluded sentences in controls (2% total). This cutoff was chosen based on the first author's perception of meaningful slowing when evaluating the recordings and differences in speaking rates. This cutoff was slightly longer than previous work (Dahl & Stepp, 2021), as PwPD have been previously shown to have a longer pause duration than typical controls (Forrest et al., 1998; Whitfield et al., 2019). The purpose of removing these sentences was that an increase in time spent reading the incongruent sentences could diminish the desired effect of the working memory task on speech production (Berthold & Jameson, 1999). Stimuli used to calculate pause duration and articulation rate included all original sentences.

Acoustic Analysis

Voice Quality

To calculate CPP and L/H ratio, we used a combination of Kay PENTAX Analysis of Dysphonia in Speech and Voice (ADSV; Awan, 2011) and MATLAB scripts. First, a custom MATLAB script was used to normalize for peak amplitude and remove pauses from each sentence. The normalized and concatenated signal was then analyzed using ADSV (Awan, 2011) to automatically calculate CPP and L/H ratio. CPP is an acoustic measure that relates to overall severity of dysphonia. The periodic harmonic peaks in the spectrum are represented by the first large peak and its accompanying harmonics in the cepstrum. The height, or prominence, of the first peak relative to the overall cepstrum is described as the CPP; higher values correspond to more pressed voice production, whereas lower values correspond to breathier voice production. The L/H ratio measures the ratio of low (< 4000 Hz) to high (> 4000 Hz) spectral energy in the speech signal; higher values of L/H ratio correspond to voices with less energy in higher frequencies.

RFF is an acoustic measure of changes in instantaneous f_o across the 10 voicing cycles preceding and following a voiceless consonant; lower values of RFF may be indicative of increased laryngeal tension. The raw speech samples were manually analyzed for RFF using the acoustic analysis software Praat, Version 6.1 (Boersma, 2022). Manual RFF calculations for each sentence were completed by a trained technician (four trained technicians total: each completing 22%, 39%, 28%, and 11% of the total sample tokens). Each trained technician inspected the acoustic waveforms to identify the 10 glottal cycles closest to the boundaries of a voiceless consonant. The 10 cycles preceding voiceless consonant are defined as RFF offset, whereas the 10 cycles following the voiceless consonant are defined as RFF onset. The period (seconds) of each cycle was then calculated. Taking the inverse of the period, we obtained the instantaneous f_o (Hz) of each cycle and compared this to the reference cycle (a reference f_o either Offset Cycle One or Onset Cycle 10) to calculate the RFF for each (in semitones [ST]; see Equation 1).

$$\text{RFF (ST)} = 39.86 \times \log_{10}\left(\frac{\text{cycle}\, f_o}{\text{reference}\, f_o}\right) \quad (1)$$

To measure RFF, we used vowel–voiceless consonant–vowel combinations (e.g., /upoʊ/ in "new posters") embedded throughout the 12 sentences for a total of 68 potential RFF tokens per participant. RFF tokens were rejected based on criteria that would have prevented valid estimation of RFF. These included but were not limited to voicing of the voiceless consonant (14%) and errors during token production (5.7%). Rejections resulted in an average of 38 offset and 42 onset usable tokens per participant in PwPD and an average of 41 offset and 38 onset usable tokens per participant in controls. Following individual calculations and rejections, mean RFF onset and mean RFF offset for each participant and each condition were calculated.

Intrarater reliability was calculated by each trained technician reanalyzing 10% of their completed RFF tokens. Two-way intraclass correlation coefficients (ICCs) were computed for intrarater reliability for RFF, resulting in ICC (2, k, absolute) ranging from .96 to .99. To calculate interrater reliability of RFF, all four trained technicians each analyzed a shared set of 10% of the total sample, resulting in ICC (2, k, absolute) = .86.

Prosody

Using the amplitude-normalized, pause-removed sentences, the *SD* of f_o for each sentence was calculated using a custom-built Praat script; lower f_o *SD* may indicate decreased intonational variation. These values were converted from Hz to ST to account for variability in speaker-to-speaker mean f_o (see Equation 2).

$$f_o\, SD\, \text{(ST)} = 12 \times \log_2\left(\frac{\text{mean}\, f_o + SD\, f_o}{\text{mean}\, f_o}\right) \quad (2)$$

The first author ran this custom-built Praat script to obtain the f_o *SD* values for all samples. The first author manually completed reanalysis in Praat for 10% of the overall sample to test intrarater reliability, resulting in ICC (2, k, absolute) = .96. To calculate interrater reliability, a trained technician completed manual analysis in Praat for 10% of total samples of f_o *SD*, resulting in ICC (2, k, absolute) = .88.

Articulation rate was manually calculated by dividing the number of syllables by the duration of all speech samples, using the pause-removed speech samples. Syllables were manually counted by the first author and divided by time (in seconds) for each sentence. Pause duration was measured by condition for each participant using a MATLAB script. In MATLAB, the first author manually selected an appropriate voicing threshold based on the stimuli waveform for each participant for each condition. Areas in the waveform that were clear silences were inspected, and the operator zoomed in to low-amplitude speech segments to ensure that the envelope selected did not include any low-amplitude speech. This voicing threshold considered pause strictly as silences other than consonant stop gaps. Following the manual selection of this cutoff, each interval in which energy in the speech signal fell below that threshold was defined as a pause. To find pause duration, the script computed the total pause time in each sentence by summing all intervals defined as a pause. This total sentence pause time was then divided by the total number of pause intervals, to obtain the average pause duration for each sentence. The average of the mean pause duration was then computed for all sentences and averaged across condition for each participant.

Intrarater reliability was calculated by the first author reanalyzing 10% of the total sample, resulting in

ICC (2, *k*, absolute) = .98 for articulation rate, and ICC (2, *k*, absolute) = .98 for pause duration. Interrater reliability was calculated by the second author analyzing 10% of total samples for both articulation rate and pause duration, resulting in ICC (2, *k*, absolute) = .95 for articulation rate, and ICC (2, *k*, absolute) = .97 for pause duration.

Articulatory Clarity

Using pause-removed speech samples in Praat, two trained technicians extracted the first two vowel formants (F_1 and F_2) from all vowels within each sentence (one technician completed 28% and the other technician completed 72% of the total samples). A semi-automated MATLAB script used these formant frequencies to calculate AAVS as the square root of the generalized variance of F_1 and F_2 formants across running speech (Whitfield & Goberman, 2014); lower AAVS indicates reduced range of motion of speech articulators.

Intrarater reliability of AAVS analysis was assessed by each technician reanalyzing 10% of their initial sample, resulting in ICCs (2, *k*, absolute) of .85 and .94. To assess interrater reliability, the two trained technicians each analyzed the same set of 10% of samples, resulting in ICC (2, *k*, absolute) = .94.

Speech Coordination

To measure VOT, we used a single vowel–plosive–vowel combination (e.g., /upoʊ/ in "new posters") from each of the 12 sentences, using the raw speech samples, for a total of 12 potential VOT instances per participant. These combinations all contained the same unvoiced plosive (/p/) and varied by vowel (/u/, /oʊ/, /ɑ/, or /eɪ/).

VOT was defined as the duration (ms) of the period between the onset of the burst from the plosive release and the start of voicing of the vowel; reduced mean VOT and increased VOT variability may reflect reduced interarticulator coordination. The first author identified both the plosive burst and the first voicing cycle of the vowel by visual inspection of the waveform in Praat. Speech samples were excluded if the plosive burst was absent from the signal (5%) or if the participant spoke the incorrect words (0.4%). Exclusions resulted in an average of 11.4 usable samples per participant in PwPD and an average of 11.3 usable samples per participant in controls. Following the extraction of VOT values, mean VOT was determined by averaging VOT by condition for each participant and VOT variability was calculated as the *SD* of VOT by condition for each participant.

Intrarater reliability of mean VOT was assessed by the first author reanalyzing 10% of the sample, resulting in ICC (2, *k*, absolute) = .86. The first and second authors also each completed analysis of the same set of VOT samples, composed of 10% of the overall sample, resulting in interrater reliability of ICC (2, *k*, absolute) = .93.

Statistical Analysis

Two three-way repeated-measures factorial analyses of variance (ANOVAs) were performed to test the effects of group, condition, voicing cycle (1–10), and their interactions for RFF onset (ST) and RFF offset (ST). Eight two-way mixed model ANOVAs were implemented to test effects of group (PwPD, controls), condition (congruent, incongruent), and their interaction on each remaining acoustic parameter: CPP (dB), L/H ratio (dB), f_o *SD* (ST), articulation rate (syllables/s), pause duration (s), AAVS (Hz^2), mean VOT (ms), and VOT variability (ms). Speaker was entered as a random intercept term for all models. All statistical analyses were conducted using R, with a statistical significance set a priori to $p < .05$. Effect sizes for significant effects were calculated as partial eta squared (η_p^2) and designated as small (.01), medium (.09), and large (.25; Witte & Witte, 2017).

Results

The results of the ANOVAs are shown in Tables 2–5 and figures can be found in Supplemental Material S1. Specific findings are detailed below.

Voice Quality

The two-way ANOVAs on CPP and L/H ratio both showed a small statistically significant effect of group, with lower CPP and higher L/H ratio in PwPD relative to controls. CPP also showed a small statistically significant effect of condition, with higher CPP values during the incongruent condition relative to the congruent condition. L/H ratio did not show an effect of condition, and neither CPP nor L/H ratio showed an interaction between group and condition. Both three-way ANOVAs on mean RFF offset and onset found large statistically significant effects of cycle. Results for the two measures otherwise diverged. There was a small statistically significant effect of condition on RFF offset, with lower RFF offset values during the incongruent condition relative to the congruent condition. There was a small significant effect of group on RFF onset, with lower values in PwPD relative to controls. Additionally, we saw a small significant effect of the interaction between group and cycle on RFF onset, consistent with a larger group difference in RFF cycles closer to the voiceless consonant. No other factors or interactions showed statistically significant effects on RFF offset and onset.

Table 2. Results of mixed-model analyses of variances for measures related to voice quality: two two-way mixed-model analyses of variance for CPP and L/H ratio, and two 3-way mixed-model analyses of variance for RFF offset and RFF onset.

Measure	Effect	*df*	*F*	*p*	η_p^2	Effect size
CPP (dB)	Group	1	30.13	< .01*	.05	Small
	Condition	1	8.97	< .01*	.02	Small
	Group × Condition	1	0.02	.886	NS	—
L/H ratio (dB)	Group	1	58.38	< .01*	.08	Small
	Condition	1	1.54	.214	NS	—
	Group × Condition	1	0.02	.886	NS	—
RFF offset (ST)	Group	1	0.09	.768	NS	—
	Condition	1	17.05	< .01*	.02	Small
	Cycle	9	97.68	< .01*	.46	Large
	Group × Condition	1	0.89	.356	NS	—
	Group × Cycle	9	0.34	.963	NS	—
	Condition × Cycle	9	1.52	.135	NS	—
	Group × Condition × Cycle	9	0.46	.899	NS	—
RFF onset (ST)	Group	1	46.31	< .01*	.04	Small
	Condition	1	0.03	.871	NS	—
	Cycle	9	121.04	< .01*	.51	Large
	Group × Condition	1	0.09	.766	NS	—
	Group × Cycle	9	5.94	< .01*	.05	Small
	Condition × Cycle	9	0.07	1.00	NS	—
	Group × Condition × Cycle	9	0.06	1.00	NS	—

Note. CPP = cepstral peak prominence; L/H ratio = low-to-high spectral energy ratio; RFF = relative fundamental frequency; NS = not significant; — = not applicable for nonsignificant findings.

*Significant at $p < .05$.

Prosody

The two-way ANOVA on f_o *SD* showed a small statistically significant effect of group, with lower f_o *SD* in PwPD relative to controls, but with no effect of condition. Articulation rate showed a medium statistically significant effect of condition, with slower articulation rate during the incongruent condition relative to the congruent condition, but with no effect of group. Neither f_o *SD* nor articulation rate showed an interaction between group and condition. There were no significant effects of condition, group, or their interaction on pause duration.

Articulatory Clarity

The two-way ANOVA on AAVS showed a small statistically significant effect of group, with lower AAVS in PwPD relative to controls. However, AAVS did not show an effect of condition or an interaction between group and condition.

Table 3. Results of two-way mixed-model analyses of variance for measures related to prosody: fundamental frequency variability (f_o *SD*), articulation rate, and pause duration.

Measure	Effect	*df*	*F*	*p*	η_p^2	Effect size
f_o *SD* (Hz)	Group	1	17.10	< .01*	.03	Small
	Condition	1	0.00	.986	NS	—
	Group × Condition	1	0.34	.556	NS	—
Articulation rate (syllables/s)	Group	1	0.35	.554	NS	—
	Condition	1	11.46	< .01*	.09	Medium
	Group × Condition	1	0.000	.734	NS	—
Pause duration (s)	Group	1	0.09	.756	NS	—
	Condition	1	2.65	.106	NS	—
	Group × Condition	1	0.05	.817	NS	—

Note. NS = not significant; — = not applicable for nonsignificant findings.

*Significant at $p < .05$.

Table 4. Results of the two-way mixed-model analysis of variance for AAVS.

Measure	Effect	*df*	*F*	*p*	η_p^2	Effect size
AAVS (Hz^2)	Group	1	31.15	< .01*	.05	Small
	Condition	1	0.43	.510	NS	—
	Group × Condition	1	0.11	.738	NS	—

Note. AAVS = articulatory acoustic vowel space; NS = not significant; — = not applicable for nonsignificant findings.
*Significant at $p < .05$.

Speech Coordination

The two-way ANOVA on mean VOT showed a medium statistically significant effect of group, with lower mean VOT values in PwPD relative to controls. Mean VOT did not show an effect of condition or an interaction between group and condition. There was no effect of group, condition, or the interaction between group and condition on VOT variability.

Discussion

The purpose of this study was to understand the effect of a concurrent working memory task on voice quality, prosody, articulatory clarity, and speech coordination in PwPD. All measures except for VOT variability and pause duration differed between people with and without PD. CPP, articulation rate, and RFF differed as a function of working memory demands, whereas L/H ratio, f_o *SD*, pause duration, AAVS, mean VOT, and VOT variability did not. However, contrary to our overarching hypothesis, no measures indicated disparate effects of working memory demands as a function of group.

Voice Quality

PwPD are often known to have breathy voices (Skodda, 2011; Skodda et al., 2013). Lower CPP and lower L/H ratios have been associated with the use of a breathy voice (Heman-Ackah et al., 2002; Jannetts & Lowit, 2014; E. A. Peterson et al., 2013), and an increased CPP and a lower L/H ratio have been associated with the use of a pressed voice (MacPherson et al., 2017). Our results showed lower CPP and higher L/H ratio values in PwPD relative to controls, suggesting the production of a weaker voice. Speakers with PD overall had CAPE-V ratings ranging from no dysphonia to mild levels of dysphonia, with similar ratings across all percepts. Their mild levels of breathiness and roughness are consistent with their low CPP values relative to control speakers. The mild levels of strain are less clearly explained by the group differences, since strain and effort have been associated with conflicting changes in CPP and L/H ratio (Anand et al., 2019; Lopes et al., 2019; Lowell et al., 2012; Nguyen & Madill, 2023). Our results also showed a significant effect of condition on CPP, with higher CPP values under the effect of the working memory task, and no significant effect of condition on L/H ratio, although we saw a trend for lower L/H ratio under the effect of the working memory task. The lack of a significant effect of condition on L/H ratio makes it difficult to evaluate the impact of changes in CPP during the working memory task, as L/H ratio and CPP more clearly explain voice quality together, rather than individually. The significant increase in CPP and trend for decreased L/H ratio during the working memory task suggests that individuals may have been using a slightly stronger voice under this increased cognitive load. Although we initially hypothesized that the increased cognitive load would increase symptoms of dysarthria, instead these results suggest the opposite.

Table 5. Results of two-way mixed-model analyses of variance for mean voice onset time (mean VOT) and VOT variability.

Measure	Effect	*df*	*F*	*P*	η_p^2	Effect size
Mean VOT (ms)	Group	1	12.88	< .01*	.11	Medium
	Condition	1	0.05	.820	NS	—
	Group × Condition	1	0.24	.625	NS	—
VOT variability (ms)	Group	1	0.59	.445	NS	—
	Condition	1	0.35	.554	NS	—
	Group × Condition	1	0.63	.429	NS	—

Note. VOT = voice onset time; NS = not significant; — = not applicable for nonsignificant findings.
*Significant at $p < .05$.

Changes in voice quality in PwPD also include increased vocal strain (Song et al., 2023), consistent with lower RFF values in PwPD (Goberman & Blomgren, 2008; Stepp, 2013; Vojtech & Stepp, 2022). We found a significant effect of group on RFF onset, with lower RFF values in PwPD relative to controls, yet we did not find a significant effect of group on RFF offset. Previous research has examined RFF in PwPD; however, it has not been consistent in design or results. For example, Goberman and Blomgren (2008) found group differences in both RFF onset and offset, but the sample size was smaller than ours (nine PwPD compared to the current study with 27 PwPD). Stepp (2013) found lower RFF values in PwPD relative to controls, yet the authors analyzed offset and onset together, whereas we independently analyzed RFF offset and RFF onset. Finally, Vojtech and Stepp (2022) examined only RFF offset in PwPD and found lower RFF offset values in PwPD relative to controls, yet this was during the presence of a transnasal endoscope, which may increase hyperfunctional behaviors, perhaps contributing to the differential behavior between groups. Although differing in study designs, we did find similar trends in RFF to previous research (lower RFF onset in PwPD relative to controls).

Previous research examining the effect of a working memory task in speakers with and without vocal hyperfunction found small yet significant effects of the task for both RFF offset and RFF onset (Dahl & Stepp, 2023). However, a similar research design observing typical speakers found an effect of working memory task condition for RFF offset, not onset (Dahl & Stepp, 2021). Similarly, our research showed a significant effect of condition on RFF offset, with lower RFF values under the effect of the working memory task, yet we did not find a significant effect of condition on RFF onset. Recent models have attempted to describe differences between RFF offset and RFF onset (Eadie & Stepp, 2013; Heller Murray et al., 2017). These models propose two types of tension: transverse tension, in which vocal folds are more tightly adducted (Hillman et al., 1989), and longitudinal tension, a result of increased cricothyroid and/or thyroarytenoid activation (Stevens, 1977). Heller Murray et al. (2017) suggested that longitudinal tension and/or a combination of both longitudinal and transverse tension may result in reduced RFF values. However, longitudinal tension alone may prevent the vocal folds from fully adducting at voicing onset. The aerodynamics associated with this incomplete adduction may preclude a decrease in RFF onset. Perhaps both speakers with and without PD use more longitudinal tension without any changes in transverse tension during a cognitive load task, thus explaining the significant difference found under the effect of the working memory task on RFF offset but not RFF onset, both in the current study and in young adults with typical voices (Dahl & Stepp, 2021). This interpretation is, however, quite speculative based on our results, which rely on acoustics changes only (with small effect sizes).

Prosody

A common characteristic of PwPD is decreased intonational variation, typically seen as lowered f_o *SD* (Bowen et al., 2013; Bunton & Keintz, 2008; Skodda, 2011). Our results confirmed this, finding a statistically significant effect of group, with lower f_o *SD* in PwPD relative to controls. In the context of cognitive stress or dual tasking, previous research has found increased f_o *SD* in those with typical speech (Boyer et al., 2018; Lively et al., 1993; Mendoza & Carballo, 1998), but no change in PwPD (Whitfield et al., 2019). Similarly, our research did not find a statistically significant effect of the working memory task on f_o *SD*.

Previous research has reported contradictory results in relation to articulatory rate in PwPD (Skodda & Schlegel, 2008; Tjaden & Wilding, 2011); our study adds to this literature, finding no group effect on articulatory rate. Studies using a dual-tasking paradigm in PwPD found no significant effect of condition on articulation rate in PwPD (Fournet et al., 2022; Whitfield et al., 2019). However, with the use of a working memory task, we did find a statistically significant effect of condition on articulatory rate, with slower rates under the effect of the working memory task. This significant reduction in articulation rate under increased cognitive load has been well established in speakers with typical speech (Berthold & Jameson, 1999) and may be explained as a simple cognitive interference.

Finally, we found no effects of group, condition, or their interaction on mean pause duration. This is relatively unsurprising—contradictory results have been reported in relation to pause duration in PwPD (Skodda & Schlegel, 2008; Tjaden & Wilding, 2011). Further, although a previous study reported that increased cognitive load was associated with increased pause duration in neurologically typical speakers (Khawaja et al., 2008), Whitfield et al. (2019) did not find an effect of group or condition on pause duration during a dual-task paradigm in people with or without PD.

Articulatory Clarity

PwPD are known to have a reduced range of motion of speech articulators (Pawlukowska et al., 2015; Rusz et al., 2013; Tjaden et al., 2013), often quantified by reduced vowel space area or AAVS (Whitfield & Goberman, 2014). In Whitfield and Goberman (2014), they found significant reductions in AAVS values in a sample size of 12 PwPD with dysarthria. Our results confirmed this, showing a significant effect of group, with lower AAVS in PwPD relative to controls. Likewise, previous research has found decreased vowel space area in neurologically typical speakers under increased cognitive stress (Hasegawa-Johnson et al., 2003; Tjaden et al., 2013). Additionally, Whitfield and Goberman (2014) showed that AAVS specifically was sensitive to condition changes, with clear speech showing higher AAVS values relative to typical speech, with large effect sizes. However, Whitfield et al. (2019) found no statistically significant effect of dual tasking on AAVS in PwPD and controls. Perhaps the change one may expect due to a cognitive load, such as dual tasking or a working memory task, is small, and AAVS may not be adequately sensitive to these changes.

Speech Coordination

PwPD are known to have difficulty with coordinating speech articulators, which is reflected in reductions in mean VOT (Darley et al., 1969; Lisker & Abramson, 1964; Morris, 1989; Richardson et al., 2014) and suspected increases in VOT variability (Darling & Huber, 2011). Our results partially confirmed this. We found a statistically significant effect of group on mean VOT, with reductions in mean VOT in PwPD compared to controls, but did not find a significant effect of group on VOT variability. Darling and Huber (2011) found significantly larger lip aperture variability in a group of nine PwPD relative to controls, reflecting the variability in articulatory coordination. As we did not find a significant effect of group on VOT variability, perhaps laryngeal–articulatory coordination is not impaired in PwPD. Another explanation may be that VOT better characterizes laryngeal rigidity in PwPD, rather than incoordination. If individuals with PD have increased laryngeal rigidity, we would expect mean VOT reductions and no difference in VOT variability, as vocal fold closure would occur faster (Goberman & Blomgren, 2008; Weismer, 1984), which is indeed what we found. Further research should confirm these findings in PwPD and establish agreement across VOT results in this population. Previous research has found contrasting results on mean VOT under divided attention cognitive stress tasks in neurologically typical speakers (Casini et al., 2009; Chiu et al., 2020); however, VOT variability has yet to be examined in the context of a working memory task. We found no significant effect of condition on mean VOT or VOT variability under the effect of the working memory task.

Clinical Implications

Our goal in this study was to determine whether a concurrent working memory task would exacerbate preexisting or subclinical symptoms of dysarthria in PwPD to aid in early identification of PD and/or symptoms of dysarthria in PD. Speech production is often affected prior to the diagnosis of PD (Kotz et al., 2009), so speech acoustics could be an important avenue in early identification of PD (Harel et al., 2004; Lim et al., 2022). Previous literature has observed dual tasking in PwPD to significantly diminish task performance related to limb motor function, including gait and upper limb movements (O'Shea et al., 2002; Talland & Schwab, 1964). Yet, Whitfield et al. (2019) found that a dual, manual motor and reading task produced little-to-no effect on speech acoustics in PwPD, although changes in limb performance under the dual-task condition in PwPD were noted. Researchers have found that, across most acoustic parameters, speech and limb motor symptoms are not correlated in PD (Brabenec et al., 2017). As motor impairments but not speech impairments are exacerbated under this increased cognitive load in PwPD, these results may imply distinct mechanisms for speech and limb motor symptoms in PD (Braak et al., 2003). This may demonstrate that the nature of speech problems in PwPD may not be affected by cognitive impairment, whereas reduced cognition significantly affects symptoms related to limb motor control (Christofoletti et al., 2016; Paul et al., 2013).

The effect of a concurrent task on acoustic metrics of speech production tasks is variable in current literature (Adams et al., 2010; Ho et al., 2002; Whitfield et al., 2019). This may be related to the nature of the secondary concurrent tasks employed, since several factors may mediate the effect of concurrent tasks on speech production: the difficulty of the tasks, the degree of resource sharing, and the allocation of resources (Broeker et al., 2021; Cutson, 1994; Fisk et al., 1986). For instance, Whitfield et al. (2019) found no changes in speech production using a simple handwriting and speaking task, whereas the more complex secondary visuo-manual tracking task described in Ho et al. (2002) elicited changes in speech production. Perhaps, the concurrent working memory task used in the present study was too simple, which would explain why no measures of speech showed a differential effect of cognitive load in PD. The degree of resource sharing between the two shared tasks also may affect outcomes; the more related two tasks are, the more resources are shared, and therefore, the greater the potential for interference between shared resources. The lack of overlap between the simple handwriting task and speaking task used in Whitfield et al. (2019) potentially accounts for the lack of changes in speech production. Conversely, researchers have found dual tasking using two motor tasks in PwPD to significantly diminish task performance (O'Shea et al., 2002; Talland & Schwab, 1964). This may be due to interference between shared resources, therefore eliciting greater change during the dual-task paradigm.

This type of interferences does not explain the findings in the present study: Despite a large level of shared resources, we did not see a differential effect of cognitive load in PD. Finally, certain characteristics of a task, such as those that may be of higher priority or seem a bigger risk of safety, require a higher level of attentional resources (Cutson, 1994). This has been described in Dromey et al. (2010), where researchers found dual-task performance, using both speech production and postural stability tasks, to cause greater changes in PwPD relative to controls, perhaps due to postural stability being of higher priority for those with PD. The present study involved an integrated response, which may have precluded the need to prioritize one task over another. Further research should investigate distinct changes to speech produced by varying concurrent task difficulty levels, the degree of resource sharing involved, and the allocation of resources.

Limitations and Future Directions

This work provides insight into speech production processes under typical conditions and under the effect of a working memory task in PwPD, but there are some limitations. We restricted our population to those without cognitive impairment, based on MoCA scores, to ensure that all participants were able to provide informed consent, and due to our inclusion of anyone with a diagnosis of PD, our sample consisted of varying levels of dysarthria. If we had focused our sample on PwPD with dysarthria or with cognitive impairment, our results may have differed. Future work focusing on speech production and cognitive load in PwPD should include more severe dysarthria ratings and those with cognitive impairments to increase the generalizability of these findings.

One limitation associated with the task itself should be noted: Both groups discriminated between the ink colors with poor accuracy. It is known that PwPD have deficits in contrast sensitivity and color discrimination (Pieri et al., 2000). The effects of color discrimination are unknown in the present study; however, ensuring color contrasts are distinct in a similar working memory task would eliminate the possibility for color discrimination affecting the cognitive load. Future work should focus on extending the scope of the project, using a different working memory task to validate our findings.

To account for the number of acoustic measures analyzed in the present study, several statistical tests were conducted. We felt this was justified as each measure was chosen to address specific physiological correlates. However, this large number of statistical tests runs the risk of alpha inflation, so the findings should be interpreted with caution.

Conclusions

CPP, articulation rate, and RFF offset differed as a function of the working memory task, and all measures except VOT variability, mean pause duration, and RFF offset differed between PwPD and controls. Contrary to our overarching hypothesis, although a simultaneous cognitive task has been shown to be differentially impactful on limb motor function in PD (O'Shea et al., 2002), here no measures of speech showed a differential effect of cognitive load in PD.

Data Availability Statement

The data sets generated and/or analyzed during this study are not publicly available to protect patient confidentiality but may be available from the senior author through formal mechanisms on reasonable request.

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Appendix

Congruent Condition Sentences

Then our pal gave **blue**, **purple**, **brown**, and **red** new posters to us.
Later Marie painted **red**, **blue**, **pink**, and **green** for two paintings in a row.
Her friend Lee potted **gray**, **purple**, **green**, and **orange** new poppies for his mother.
Then our pal gave **orange**, **blue**, **purple**, and **green** new posters to us.
Later Marie painted **blue**, **pink**, **orange**, and **brown** for two paintings in a row.
Her friend Lee potted **green**, **gray**, **pink**, and **red** new poppies for his mother.
Incongruent Condition Sentences
Then our pal gave **red**, **brown**, **purple**, and **blue** new posters to us.
Later Marie painted **green**, **pink**, **blue**, and **red** for two paintings in a row.
Her friend Lee potted **orange**, **green**, **purple**, and **gray** new poppies for his mother.
Then our pal gave **blue**, **orange**, **green**, and **purple** new posters to us.
Later Marie painted **orange**, **brown**, **blue**, and **pink** for two paintings in a row.
Her friend Lee potted **gray**, **purple**, **green**, and **orange** new poppies for his mother.