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Sex Differences in the Speech of Persons With and Without Parkinson's Disease

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ABSTRACT

Background: Sex differences are apparent in the prevalence and the clinical presentation of Parkinson's disease (PD), but their effects on speech have been less studied.
Method: Speech acoustics of persons with (34 females and 34 males) and without (age- and sex-matched) PD were examined, assessing the effects of PD diagnosis and sex on ratings of dysarthria severity and acoustic measures of phonation (fundamental frequency standard deviation, smoothed cepstral peak prominence), speech rate (net syllables per second, percent pause ratio), and articulation (articulatory–acoustic vowel space, release burst precision).
Results: Most measures were affected by PD (dysarthria severity, fundamental frequency standard deviation) and sex (smoothed cepstral peak prominence, net syllables per second, percent pause ratio, articulatory–acoustic vowel space), but without interactions between them. Release burst precision was differentially affected by sex in PD. Relative to those without PD, persons with PD produced fewer plosives with a single burst: females more frequently produced multiple bursts, whereas males more frequently produced no burst at all.
Conclusions: Most metrics did not indicate that speech production is differentially affected by sex in PD. Sex was, however, associated with disparate effects on release burst precision in PD, which deserves further study.
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Parkinson's disease (PD) is most likely to be diagnosed in people over the age of 60 years (Muangpaisan et al., 2011) and is 1.5 times more likely to occur in men than in women (Picillo et al., 2017; Van Den Eeden et al., 2003). Current research suggests that the sex difference in prevalence is due to a mixture of genetic, hormonal, and environmental life factors (Cerri et al., 2019). Genetic factors may include higher urate levels or mutations in lysosome-related genes (Cerri et al., 2019). Hormonal factors may include lifetime exposure to estrogen and progesterone, two sex hormones produced by the ovaries (Adashi, 1994). These sex hormones are hypothesized to help protect against the development of PD (Gatto et al., 2014), possibly due to the protection of dopamine production and maintenance in the brain (Cerri et al., 2019; Vaidya et al., 2021) and against neuroinflammation (Cerri et al., 2019), which may be associated with more mild symptoms at the onset of PD (Vaidya et al., 2021). Environmental factors may include chronic stress (Hemmerle et al., 2012), occupational exposure to harmful substances, or lack of physical activity (Cerri et al., 2019). The above list is not exhaustive, and several factors remain controversial but serve to highlight the impact of sex on PD.

In addition to differences in prevalence as a function of sex, recently there is emerging evidence across multiple domains that the symptoms of PD differ by sex (Cerri

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et al., 2019; Picillo et al., 2017; Russillo et al., 2022; Vaidya et al., 2021). These identified sex differences include genetic risk factors (Cui et al., 2021; Y. Lee et al., 2018; Li et al., 2021; Loesch et al., 2018; Ping et al., 2018), biomarker performance (Baik et al., 2020; Cortese et al., 2018; Heller et al., 2018; Luca et al., 2022; Yang et al., 2018), treatment responses (Abraham et al., 2019; Conti et al., 2022; Golfrè Andreasi et al., 2022; Martinez-Ramirez et al., 2014; Sampaio et al., 2018; Schwarzschild et al., 2019), and both nonmotor (Balash et al., 2019; Defazio et al., 2017; Hu et al., 2018; Nicoletti et al., 2017; Raciti et al., 2020; Wandner et al., 2012) and motor (Cho et al., 2019; Kang et al., 2022; Picillo et al., 2022; J. Y. Shin et al., 2016; Wan et al., 2022) symptoms. Although sex differences in PD have not yet been examined for speech production, a rationale for such differences is supported by the known sex differences in motor symptoms (Haaxma et al., 2007; Kim et al., 2018). One common classification system based on subitems of the Movement Disorder Society's Unified Parkinson's Disorder Rating Scale (UPDRS) classifies persons with PD as having tremor dominant (TD), postural instability and gait disturbance (PIGD), or indeterminant subtypes (Stebbins et al., 2013). Motor subtype may be linked with differences in the number and type of speech symptoms a person develops (Brown & Spencer, 2020; Dumican & Watts, 2020; Tykalová et al., 2020). Persons with PIGD subtypes tend to experience more speech deficits than persons with TD subtypes (Dumican & Watts, 2020; Tykalová et al., 2020). When considered together with sex differences in motor subtypes where females tend to present with a TD subtype (Haaxma et al., 2007) and males tend to present with a PIGD subtype (Kim et al., 2018), males with PD may present with more speech deficits or greater severity of speech deficits than females with PD.

At least 70% of persons with PD develop speech impairments (Hartelius & Svensson, 1994; Miller et al., 2007; Schalling et al., 2017) that may affect phonation, speech rate, and articulation. Changes in speech may develop relatively early in the disease but may be too subtle to detect (Sapir, 2014). Detection of speech symptoms in persons with PD often relies on the perception of a change, whether the perception is identified by the self (Schalling et al., 2017) or others (Miller et al., 2007). Because self-perception of speech is impaired in PD (Clark et al., 2014; Ho et al., 2000) and listeners are often able to accommodate a variety of speech differences due to categorical perception (Kong & Edwards, 2016; Perkell et al., 2004), small changes in speech production may be best quantified using acoustic measures to query subclinical differences in the phonation, speech rate, and articulation of persons with PD.

Phonation, speech rate, and articulation are also influenced by the speaker's sex (Munson & Babel, 2019). Sex differences stem from differences in anatomy and physiology (e.g., vocal tract length; Kahane, 1982; Vorperian et al., 2009), environmental factors (e.g., occupational noise exposure and hearing loss; Helzner et al., 2005), and cultural expectations (Munson & Babel, 2019). Females without PD tend to produce higher cepstral peak prominences (CPP; Awan et al., 2012; Rusz et al., 2022), larger vowel spaces (R. A. Fox & Jacewicz, 2008; Houle & Levi, 2020; Neel, 2008; Sharifzadeh et al., 2012), and more precise consonants (Rusz et al., 2022; Whiteside, 1996; Whiteside & Marshall, 2001) than males without PD. Sex differences in fundamental frequency (f_o) standard deviation (*SD*; Clopper & Smiljanic, 2011; Fitzsimons et al., 2001; Traunmüller & Eriksson, 1995) and speech rate (Bóna, 2014; Clopper & Smiljanic, 2011; Jacewicz et al., 2009, 2010) are inconsistent across studies.

Inconsistent sex effects for specific acoustic measures may be related to aging (Bóna, 2014; Jacewicz et al., 2009, 2010), speech task (e.g., monologue vs. standard reading passage; Bóna, 2014; Jacewicz et al., 2009, 2010), and language or dialect differences (Clopper & Smiljanic, 2011; Jacewicz et al., 2009, 2010; Traunmüller & Eriksson, 1995). Despite the variation, changes in f_o *SD* and speech rate are commonly examined in the speech of persons with PD. Given the influence of sex on speech production and sex differences in motor function in persons with PD, it is critical to investigate sex differences in the speech of persons with PD as compared to age- and sex-matched persons without PD.

Clinical Perceptions of Speech in Persons With PD

Persons with PD may develop speech symptoms characteristic of hypokinetic dysarthria (Darley et al., 1969b; Sapir, 2014). Speech symptoms in persons with PD may vary widely, and as many as 38 perceptual dimensions of speech have been investigated (Darley et al., 1969a; Wannberg et al., 2016). Assessing so many perceptual dimensions provides clinically relevant information on specific declines in function but is also time-consuming. Shorter protocols may provide similar information on domain-specific impairments or overall severity of impairment (Wannberg et al., 2016). Three of the most commonly identified domains affected by PD are phonation, speech rate, and articulation (Darley et al., 1969a; Logemann et al., 1978; Wannberg et al., 2016). Phonation has been suggested as the first domain affected by PD (Ho et al., 1998; Logemann et al., 1978; Ma et al., 2020). Other domains are rarely affected without a concomitant change to phonation (Ho et al., 1998; Logemann et al., 1978; Wannberg et al., 2016). This is also consistent with the model of PD progression outlined by Braak et al.

(2004). Confirming these reports is difficult as persons with PD may use compensatory strategies to mask declines in speech production (Sapir, 2014). Taken together, obtaining gestalt clinical ratings of the overall severity of dysarthria can be effective in capturing clinically relevant symptoms (Stipancic et al., 2016, 2021). However, additional use of acoustic measures may facilitate the identification of subclinical symptoms that are either not perceptible or are masked by compensatory strategies.

Measures of Phonation

Changes to laryngeal function are one of the most commonly described speech impairments in persons with PD (Logemann et al., 1978; Schalling et al., 2017). Although a variety of instrumentation is used to analyze changes in function, such as electromyography (Gallena et al., 2001; Hirose, 1986) and videoendoscopy (Gallena et al., 2001; Hirose, 1986; Perez et al., 1996), speech acoustics provide a noninvasive window into laryngeal function and are thus more ubiquitous across studies. Here, we will focus on two acoustic measures of phonation: f_o *SD* and smoothed CPP (CPPS).

The acoustic measure f_o *SD* is lower in persons with PD than age- and sex-matched persons without PD (Bowen et al., 2013; Goberman et al., 2005; Holmes et al., 2000; Rektorova et al., 2016; Rusz et al., 2011; Skodda, Visser, & Schlegel, 2011). This reduced pitch variability is often described as being monopitched. Speakers who have a smaller f_o *SD* or are perceived as monopitched are likely to also be perceived as less natural sounding (Anand & Stepp, 2015) or less intelligible (Frota et al., 2021; Plowman-Prine et al., 2009) than speakers with a larger f_o *SD*.

Both females and males with PD may experience reductions in f_o *SD* when compared to age- and sex-matched persons without PD (Holmes et al., 2000; Rusz et al., 2022; Skodda, Visser, & Schlegel, 2011), but it is unclear whether females and males with PD experience similar changes in f_o *SD*. One reason may be the speech task itself as differences in emotional content and syntactic structures may elicit different f_o *SD*s (e.g., monologue vs. structured reading passage). Additionally, methodological differences in the analysis of sex differences in persons with PD have contributed. Given the sex difference in the prevalence of PD (Picillo et al., 2017), it may be difficult to recruit participants to create balanced, sex- and age-matched groups of persons with and without PD. To account for this challenge, studies may include unbalanced designs (Bowen et al., 2013; Rusz et al., 2022), subset data, and run separate analyses for female and male participants (Skodda, Visser, & Schlegel, 2011), or use small sample sizes (MacPherson et al., 2011). As a result, it remains unclear whether f_o *SD* changes similarly between females and males with PD compared to age- and sex-matched persons without PD (Bowen et al., 2013; MacPherson et al., 2011; Skodda, Visser, & Schlegel, 2011).

In addition to changes to pitch variability, voice quality is implicated in PD. Logemann and Fisher (1981) reported that 89% of persons with PD had impairments to voice quality. Persons with PD may be perceived as having increased roughness, breathiness, or instability. Overall, persons with PD are perceived to have more severe dysphonia than persons without PD (Bauer et al., 2011; Silva et al., 2012; Holmes et al., 2000; Logemann & Fisher, 1981; Midi et al., 2008). Several measures have been investigated (e.g., jitter), but we will focus on cepstral measures. Cepstral measures, such as CPP or CPPS, have a strong relationship with auditory-perceptual ratings of dysphonia (Awan et al., 2010) and are currently recommended by voice evaluation protocols (Patel et al., 2018).

An increasing number of studies examine cepstral measures in persons with PD. CPP and CPPS may be sensitive to changes in the voice quality of persons with PD, but the direction of the difference varies by study. Compared to persons without PD, persons with PD may have reduced (Šimek & Rusz, 2021), similar (Rusz et al., 2022; Šimek & Rusz, 2021), or greater (Burk & Watts, 2019) CPP or CPPS values. Inconsistency across studies may be related to speech tasks since cepstral measures are affected by phonetic context (Šimek & Rusz, 2021). Additionally, there are sex differences. Males without PD are reported to have higher CPP or CPPS values than females without PD (Awan et al., 2012; Chen et al., 2010). In contrast, Rusz et al. (2022) investigated cepstral measures in persons with and without PD and reported that females with and without PD produced higher CPP values than males with and without PD. It is unclear why these results conflicted with previous findings (Awan et al., 2012; Chen et al., 2010), but CPP values were within the healthy range for nondysphonic speakers (Murton et al., 2020). Overall, cepstral measures have clinical promise but require further investigation and replication to determine their sensitivity to PD while accounting for sex differences.

Measures of Speech Rate

Persons with PD are likely to experience changes to typical speech timing, consistent with hypokinetic dysarthria, at some point during their disease progression (Galaz et al., 2016; Hartelius & Svensson, 1994; Schalling et al., 2017). Perceptions of atypical speech timing may be described as producing fast or slow speech, difficulty initiating speech, or changes to speech rhythm (Schalling et al., 2017). Despite these perceptions, when compared with age-matched persons without PD, persons with PD tend to have similar average speech rates (Galaz et al.,

2016; Skodda, 2011; Walsh & Smith, 2012). It is possible that examining speech rate without accounting for pauses does not account for differences in speech timing between persons with and without PD.

Bandini et al. (2015) used several measures of speech rate when investigating timing in persons with and without PD. Recordings of repeated sentences were analyzed for measures of sentence duration, intersentence duration, intrasentence pauses, and the net speech rate. Net speech rate was defined as the sum of the sentence durations minus the inter- and intrasentence pauses, divided by the number of sentences. The results indicated that there were no differences in the total sentence durations even though pause durations and net speech rates differed. Compared with persons without PD, persons with PD used faster net speech rates but longer pauses within and between sentences (Bandini et al., 2015). This suggests that persons with PD alter their speech timing by altering both net speech rate and pause duration.

Pauses may provide a unique opportunity to examine the timing of speech initiation and termination. To accommodate age-related changes in cognitive and respiratory function, older speakers may increase the frequency and duration of their pauses. These pauses often occur at syntactic boundaries (Huber et al., 2012). Persons with PD also increase their pause frequency and duration (Bandini et al., 2015; Goberman et al., 2005; Huber et al., 2012; Skodda, Grönheit, & Schlegel, 2011; Whitfield & Gravelin, 2019), but pauses may occur at locations unrelated to syntactic boundaries (Huber et al., 2012). Huber et al. (2012) suggested that, beyond age-related changes, cognitive–linguistic declines associated with PD contribute to the placement and increased use of pauses. Given sex differences in the patterns of cognitive declines in persons with PD (Cerri et al., 2019; Cholerton et al., 2018; Szewczyk-Krolikowski et al., 2014), speech timing in females and males with PD may be differentially affected.

Measures of Articulation

In addition to changes in laryngeal function and speech rate, persons with PD are likely to produce speech errors (Logemann & Fisher, 1981; Logemann et al., 1978). Declines in articulation are often attributed to difficulties with rapid movements of the articulators and weaker articulatory contacts, consistent with hypokinetic dysarthria (Miller, 2017; Sapir, 2014). These changes affect both vowel and consonant production.

In general, persons with PD have similar or smaller vowel spaces than persons without PD (Skodda et al., 2012; Whitfield & Goberman, 2014; Whitfield & Mehta, 2019). Smaller vowel spaces suggest less vowel differentiation, and speech may be perceived as less intelligible (Whitfield & Goberman, 2014). Vowel space differences often depend on the measure used. Whitfield and Mehta (2019) recommend the use of the articulatory–acoustic vowel space (AAVS) in persons with PD. The AAVS accounts for vowel productions on the outer edge of the vowel space as well as the overall distribution of F1 and F2 formant data. It is sensitive to within-speaker changes between habitual and clear speech (Whitfield & Mehta, 2019) and changes related to PD (Mefferd, 2015; Whitfield & Mehta, 2019).

The AAVS is also sensitive to speaker sex (Whitfield & Goberman, 2014; Whitfield & Mehta, 2019). On average, females have larger AAVS values than males. This is unsurprising given the sex differences in formant frequencies between females and males (R. A. Fox & Jacewicz, 2008; Houle & Levi, 2020; Neel, 2008; Sharifzadeh et al., 2012), even when formant frequencies are normalized (e.g., converted linear Hertz scale to a logarithmic Bark scale; Houle & Levi, 2020; Neel, 2008).

In addition to vowel production, persons with PD tend to exhibit changes in plosive consonant production (Ackermann & Ziegler, 1991; Logemann & Fisher, 1981). Using auditory-perceptual measures of speech accuracy, Logemann and Fisher (1981) reported that in a sample of 200 persons with PD, 90 produced some kind of speech error, all with difficulties on plosives. Plosives were typically replaced by fricatives made with the same place of articulation and voicing (e.g., /k/ was replaced by the velar, voiceless fricative /x/; Logemann & Fisher, 1981). This pattern suggests that persons with PD have difficulties building air pressure required to produce plosives, possibly the result of a decreased ability to maintain an oral or velar constriction. Acoustic analyses of plosives typically focus on voice onset time (e.g., Fischer & Goberman, 2010; Tykalova et al., 2017), but Parveen and Goberman (2014) investigated the release burst. Specifically, they examined the frequency of prototypical single bursts (high precision) relative to the frequency of absent or multiple bursts (lower precision) in nine persons with PD relative to nine persons without PD. Although release burst precision declines with age (Parveen & Goberman, 2012), persons with PD were more likely to omit a release burst or to produce multiple release bursts than persons without PD (Parveen & Goberman, 2014). This indicates that, beyond age, persons with PD produce fewer prototypical release bursts (Parveen & Goberman, 2014). Given the modest sample size, speaker sex was not investigated within this study. Thus, these results must be replicated and extended to determine whether sex differences exist in the release burst precision of persons with PD.

This Study

Given the strong evidence for sex specificity in other symptoms of PD, it is important to examine sex differences in the speech features of persons with PD. This study investigates the effects of speaker group (with PD, without PD) and sex (female, male) on clinical ratings of dysarthria and acoustic measures of phonation (f_o *SD*, CPPS), speech rate (net syllables per second, percent pause ratio), and articulation (AAVS, release burst precision). Acoustic measures were chosen based on their use in prior studies. Consistent with previous findings, we hypothesized that, compared to persons without PD, persons with PD would have greater severity of dysarthria ratings, lower f_o *SD*, lower CPPS, faster net speech rates with longer pauses, smaller AAVS, and fewer prototypical release bursts. Regardless of speaker group, we expected to find sex differences such that females would have similar or less severe dysarthria ratings, larger f_o *SD*, lower CPPS, slower net speech rates with shorter pauses, larger AAVS, and more prototypical release bursts than males. We also hypothesized that speaker group and sex would interact. Given the proposed link between motor subtypes and speech deficits in persons with PD (Dumican & Watts, 2020; Tykalová et al., 2020), and sex differences in the prevalence of motor subtypes (Haaxma et al., 2007; Kim et al., 2018), we predicted that differences between females with and without PD would be smaller than the differences between males with and without PD.

Method

Informed consent was obtained from all participants, in compliance with the University of Washington Institutional Review Board or the Boston University Institutional Review Board. All participants were compensated for their time.

Participants

This retrospective study included 136 participants (34 females with PD, 34 females without PD, 34 males with PD, 34 males without PD) chosen from a corpus of speech developed from research studies conducted by the senior investigator since 2010. Participants with PD were age-matched within 3 years and sex-matched[1] to participants without PD. All participants were native speakers of English. Participants without PD denied a history of neurological impairments and language or voice disorders. Two participants without PD reported a childhood history of speech errors on the phoneme /r/ with no residual errors as perceived by the researchers. Fourteen participants with PD (seven females with PD, seven males with PD) reported a history of speech and language therapy related to their PD. Participants with PD were diagnosed by a neurologist, were receiving daily levodopa/carbidopa therapy, and were recorded during the "on" phase of their medication. One participant with PD had a deep brain stimulator implant that was turned off for the duration of the recordings. Additionally, the number of years since initial diagnosis was collected, and motor signs (Part III) were assessed by a researcher certified to administer the UPDRS. For 54 of the participants with PD, the UPDRS Part II was also assessed, and clinical subtypes were identified (see Table 1), as described by Stebbins et al. (2013).

Due to the retrospective nature of this study and differences across study protocols, not all participants completed a hearing or cognitive screening at the time of recording. We did not exclude participants based on hearing loss or cognitive decline in order to maintain the ecological validity of the study. Age-related changes in hearing may begin as young as 30 years of age (J. Lee et al., 2012), and approximately 40% of people over 65 years old have a hearing loss (Ries, 1994). Additionally, cognitive decline is a potential symptom of PD (Cerri et al., 2019), and up to 46% of persons without PD over 65 years old may have a mild cognitive impairment (Ward et al., 2012). Hearing status was assessed in two different ways due to differences in collection methods: a question about history of hearing loss or a standardized hearing screening with responses under 25 dB HL for frequencies 1 kHz and below and under 40 dB HL above 1000 Hz (Schow, 1991). Of the 136 participants, 61 (18 females with PD, 21 females without PD, 11 males with PD, 11 males without PD) passed a standardized hearing screening and 27 (four females with PD, nine females without PD, eight males with PD, six males without PD) failed. Twenty-one participants (four females with PD, three females without PD, one male with PD, 13 males without PD) reported no history of hearing loss. Seven participants (three females with PD, two males with PD, two males without PD) reported a history of a hearing disorder, of whom three used hearing aids to compensate for the loss (one female with PD, one male with PD, one male without PD). Based on this, 18 females with and without PD and 18 males with and

Table 1. Clinical subtype for persons with Parkinson's disease.

Clinical subtype	Female	Male
Tremor dominant	9	17
Postural instability/gait dominant	14	9
Indeterminate	3	2
Unavailable	8	6

[1]Only binary *sex*, *female* or *male*, and not *gender identity,* was collected from speakers at the initiation of data collection in 2010.

without PD had some degree of hearing loss. Hearing status was unknown for 20 participants (five females with PD, two females without PD, 12 males with PD, one male without PD). Of the 105 participants who completed a Montréal Cognitive Assessment (Nasreddine et al., 2005), 87 participant (19 females with PD, 29 females without PD, 22 males with PD, 17 males without PD) scored higher than a 25 out of 30 points, and the remaining 18 participants (seven females with PD, two females without PD, seven males with PD, two males without PD) scored between 21 and 25. A cognitive screening test was not obtained for 31 participants (eight females with PD, three females without PD, five males with PD, 15 males without PD).

Recording

Due to the retrospective nature of this study, the recording conditions were not consistent across participants. Some were recorded in a quiet room with a Shure WH20, WH20 XLR, or SM35XLR headset microphone connected to an Olympus Linear PCM recorder, LS-10, 2. Alternatively, participants were recorded in a sound-treated booth with an earset Shure omnidirectional MX153 microphone connected to an RME Quadmic II microphone amplifier and digitized via a soundcard (MOTU Ultralite-mk3 Hybrid sound card or RME Fireface UCX). A sampling rate of 44.1 kHz at 16-bit resolution was used for all recordings. Microphones were placed at a 45° angle and 10 cm from the lips. Participants read the first paragraph of "The Rainbow Passage" (Fairbanks, 1960) at a comfortable rate and volume and were instructed to continue reading, regardless of any errors that were produced. A standardized reading passage rather than spontaneous speech was used to control for phonetic context, syntactic structure, and emotional content.

Clinical Ratings

Ratings of dysarthria severity were obtained from five licensed speech-language pathologists, specialized in voice and motor speech disorders. Listeners completed a self-paced auditory-perceptual experiment designed and hosted in Gorilla (Anwyl-Irvine et al., 2020). Listeners were asked to wear headphones and complete the task in a quiet room. Stimuli consisted of the third and fourth sentences extracted from The Rainbow Passage and were root-mean-square amplitude normalized. Twenty-eight (approximately 20%) sound files were repeated to assess intrarater reliability, resulting in 164 experimental stimuli. The rating task took approximately 45–60 min.

Prior to the rating task, listeners were asked to adjust their computer volume to a comfortable listening level based on a speech sample from a male without PD that was not included in the study. Dysarthria was defined as possibly including changes to a speaker's vocal quality, speech rate, articulation, and loudness. Listeners were asked to make a gestalt rating of dysarthria severity using a visual analog scale with labels "No dysarthria," "Mild dysarthria," "Moderate dysarthria," and "Severe dysarthria" at approximately 0%, 33%, 66%, and 100% of the scale length, respectively (see Figure 1). Listeners were provided an opportunity to replay each stimulus. No stimulus was played more than 2 times. Once satisfied with their rating, listeners pressed "Continue" to progress to the next stimulus. Before starting the experimental task, listeners practiced using the visual analog scale using four stimuli from two females and two males without PD that were not included in the study. After this practice, the experimental stimuli were presented in a pseudorandom order, and listeners did not hear the same speaker 2 times in a row.

Reliability was analyzed using intraclass coefficient correlations (ICCs; Koo & Li, 2016). Intrarater reliability two-way ICCs for consistency were .79, .82, .83, .88, and .93 for the five raters, respectively. This was interpreted as acceptable to great intrarater reliability. Interrater reliability two-way ICC with random effects over the mean of five raters for consistency was .86, interpreted as good interrater reliability.

Acoustic Analysis

Recordings were analyzed for the following measures: f_o *SD*, CPPS, net syllables per second, percent pause ratio, AAVS, and release burst precision. All acoustic analyses were conducted using Praat 6.2.04 (Boersma & Weenink, 2021). All measures, except for CPPS, were manually extracted by two researchers. To assess the reliability of manual measures, inter- and intrarater reliability were measured from 28 (approximately 20%) sound files using ICCs. Inter- and intrarater reliability for f_o *SD*, net speech rate, pause duration, and AAVS were greater than .98 and .97, respectively, interpreted as excellent reliability. Additionally, measurement error was assessed by identifying outliers in the distributions of all continuous measures (defined as greater or less than 1.5 times the interquartile range). Outliers were remeasured and replaced if greater than 1 *SD* away from the original value. As the release burst analysis resulted in nominal data, we

Figure 1. Visual analog scale for clinical ratings of dysarthria severity.

calculated the percent agreement for the presence and number of release bursts on 28 (20%) sound files. The two raters agreed with each other 89% of the time for determining a plosive context was obligatory and 83% of the time for the number of release bursts. The two raters agreed with themselves 90% and 92% of the time for determining a plosive context was obligatory and 91% and 83% of the time for the number of bursts.

Measures of Phonation

The two measures of phonation were f_o *SD* and CPPS. Voiced segments were extracted from the reading passage using a publicly available voice detection algorithm (Maryn et al., 2010) and either saved for manual inspection or used to automatically extract CPPS. Nonmodal phonation (i.e., creaky phonation; Gordon & Ladefoged, 2001) was removed via visual inspection of the waveform of the voiced segments (accounted for 15% of the duration of the voiced segments). Measures of mean f_o and f_o *SD* were then extracted using a frequency range of 75–350 Hz for females and 50–300 Hz for males, except for seven females and seven males for whom nondefault ranges were used to improve tracking. The f_o *SD* was converted to semitones using Equation 1. Three values of f_o *SD* were identified as outliers, and one value was replaced.

$$f_o \text{ SD in Semitones} = 12 \times \log_2\left(\frac{\text{mean } f_o + f_o \text{ SD}}{\text{mean } f_o}\right) \quad (1)$$

Equation 1. Conversion of f_o *SD* measured in Hertz to semitones.

Measures of Speech Rate

As participants were encouraged to continue reading "The Rainbow Passage" disregarding any errors, each recording was transcribed to account for any additions, substitutions, and omissions of syllables and phrases. The number of syllables produced by each participant was counted by two researchers. Discrepancies were resolved through discussion until a consensus was achieved. The recordings and transcripts were aligned using the Penn Phonetics Lab Forced Aligner (Yuan & Liberman, 2008). Each sound file and corresponding TextGrid were manually inspected at a visible range of 700–800 ms. The TextGrid boundaries were manually adjusted to align with the onset and offset of speech. A customized Praat script automatically extracted speech and pause durations from the TextGrid.

Definitions for net speech rate and percent pause were consistent with previous studies (Bandini et al., 2015; Skodda et al., 2009; Skodda & Schlegel, 2008). The net speech rate was calculated as the total duration of speech produced minus the sum of all pauses, divided by the number of syllables produced. Pauses were identified as silent durations between words greater than 75 ms in duration. The cutoff was chosen to maximize the identification of pauses between words and was based on the mean within-word (with PD: 73 ms, without PD: 37 ms) and between-words silent durations (with PD: 106 ms, without PD: 81 ms) reported in previous work (Whitfield & Gravelin, 2019). There were two instances of pauses greater than 200 ms within "raindrops," which were treated as between words, rather than within a word. To calculate the percent pause ratio, pause durations were summed and divided by the total duration of the reading passage. Five values for net speech rate and five values for percent pause ratio were identified as outliers and reanalyzed. Of these outliers, zero values were replaced.

Measures of Articulation

Vowel articulation was assessed using the AAVS (Whitfield & Goberman, 2014; Whitfield & Mehta, 2019). Using a visible window of 500–600 ms, vowel boundaries placed by the forced aligner were manually inspected and adjusted to align with the onset and offset of periodic energy and a defined formant structure consistent with the target vowel with relatively steady states (e.g., omitting liquids and glides based on formant transitions and shorter durations). Vocalic "r" (i.e., /ɝ/, /ɚ/, /ɛr/, /ɔr/, /ɑr/) was included within the vowel boundaries. All segments of creaky phonation were omitted. Formant frequencies were tracked using an upper frequency limit of five formants below 5.5 kHz for females and 5 kHz for males, except for 10 females and 19 males for whom nondefault settings were used to improve tracking. Formant frequencies F1 and F2 were extracted using the Formant Listing function in Praat. The AAVS was then calculated using a customized MATLAB script based on the study of Whitfield and Goberman (2014). Six AAVS values were identified as outliers and reanalyzed. Of these outliers, two values were replaced.

One measure of consonant articulation was analyzed: release burst precision. Release burst precision was defined by the presence of an obligatory context and the number of release bursts produced during the plosive (i.e., /p/, /b/, /t/, /d/, /k/, /g/). As with the AAVS, the upper frequency limit was set to 5.5 kHz for females and 5 kHz for males. To account for the effects of coarticulation and word position (initial, medial, final), the presence of an obligatory context for the plosive was determined using two criteria: (a) the closure period, visualized as a decrease in intensity on the waveform or the lack of energy above the voice bar (above 500 Hz) on a spectrogram, and (b) a subsequent period of aperiodic energy across frequencies. Contexts that did not meet these criteria were marked

as nonobligatory. Obligatory contexts were then analyzed for the number of release bursts. A release burst was defined as the clear vertical band or bands present after the closure period and at the beginning of the aperiodic energy across all frequencies on the spectrogram. Importantly, these criteria allowed the researchers to distinguish between nonobligatory contexts and obligatory contexts with no release burst (e.g., presence of closure period with subsequent aperiodic energy across frequencies, but no visible vertical band). Release burst precision resulted in four categories: (a) nonobligatory plosive; (b) obligatory and zero bursts; (c) obligatory and prototypical, single bursts; and (d) obligatory and multiple bursts. See Figure 2 for examples of these four categories.

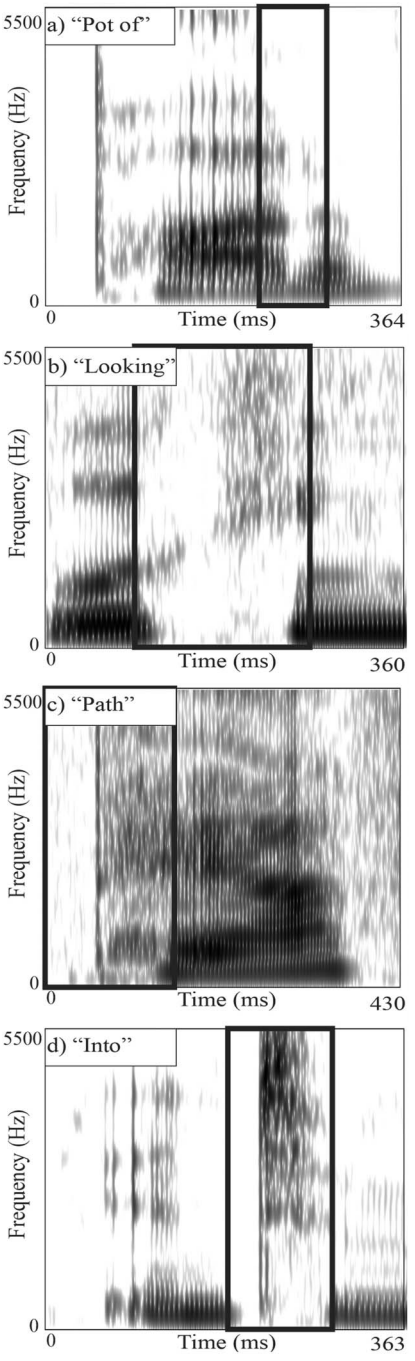
An average of 62 plosive contexts were analyzed within a sound file. All plosives were inspected using a visible window length of 200–250 ms. Of the 62 plosives contexts, 11 were marked as nonobligatory more than 85% of the time across participants, characterized by the consistent omission of either a closure period (e.g., medial /t/ in "apparently") or aperiodic energy (e.g., final /t/ in "at"). We assumed the contexts elicited similar coarticulatory effects across participants and were removed from further analysis. Three plosive contexts were excluded due to difficulty identifying whether the release burst was obligatory and, if so, determining the number of release bursts produced (e.g., /k/ in "act"). Two contexts were excluded due to poor interrater agreement (less than 65%). As a result, an average of 47 plosive contexts per speaker were used in the analysis.

Statistical Analysis

Demographic information was examined to determine group differences that may influence acoustic measures using R (RStudio Team, 2020). An **analysis of variance** (ANOVA) was used to determine if age differed across speaker group (with PD, without PD) and sex (female, male) using the Anova function from the car package (J. Fox et al., 2012). Within participants with PD, two correlations were conducted to investigate the relationships between age and time since diagnosis and age and UPDRS Part III score using the **cor.test** function from the stats package (R Core Team, 2021). Furthermore, two *t* tests were conducted to identify sex differences in the time since diagnosis and UPDRS Part III score using the **t.test** function from the stats package (R Core Team, 2021).

A multivariate analysis of covariance was conducted to investigate the main effects for speaker group, sex, and age and the two-way interaction between speaker group and sex on clinical ratings of dysarthria severity and acoustic measures of phonation (f_o *SD*, CPPS), speech rate

Figure 2. Four spectrograms are presented from a female without PD. Each spectrogram contains the phrase being produced in the upper left-hand corner, and a rectangle is used to denote the location of the plosive of interest. Each example presents a different type of release burst context. (a) The /t/ in "pot of" was identified as nonobligatory based on the lack of aperiodic energy after a closure period. (b–d) Obligatory plosive contexts, categorized as (b) zero release burst based on the lack of a clear vertical band between the closure period and subsequent aperiodic energy; (c) a prototypical, single release burst with a single vertical band between the closure period and subsequent aperiodic energy; and (d) multiple release bursts with two vertical bands between the closure period and subsequent aperiodic energy.



(net speech rate, percent pause ratio), and articulation (AAVS) using the **Manova** function from the stats package (R Core Team, 2021). Based on the wide age range of participants (48–82 years), age was included as a covariate to control for age-related changes in speech production. Clinical ratings of dysarthria were averaged across raters and were square root transformed prior to statistical analysis to reduce positive skew (toward "No dysarthria"). The transformed clinical ratings of dysarthria for persons without PD were normally distributed, but not the ratings for persons with PD. This violation was tolerated due to the large sample size included in this study. One participant was identified as an extreme outlier (i.e., percent pause ratio was approximately 50%). The model was run with and without the extreme outlier, but the results and interpretation did not change so the outlier was retained. Post hoc analyses were conducted for significant categorical main effects using the **welch_anova_test** function in the stats package (R Core Team, n.d.). Partial effect sizes, Cohen's f^2, were calculated using the **cohens_f_squared** function in the effectsize package (Ben-Shachar, Makowski, & Ludecke, 2020). Cohen's f^2 effect sizes of 0.02, 0.15, and 0.35 were interpreted as small, medium, and large effects, respectively (Ben-Shachar, Lüdecke, & Makowski, 2020; Cohen, 1992). α was set to .05 and adjusted for post hoc analyses to .025.

Chi-square tests of association were conducted to investigate the effects of speaker group and sex on the distribution of release bursts in Minitab Version 21.1 (Minitab, 2021). Separate models were used to analyze the four plosive contexts: (a) nonobligatory plosive; (b) obligatory and no burst; (c) obligatory and prototypical, single burst; and (d) obligatory and multiple bursts. When no association between speaker group and sex was supported, chi-square goodness-of-fit tests were used to examine the independent effects of speaker group or sex on plosive contexts. Pearson chi values (χ^2) are reported. Phi (ϕ) effect sizes were calculated by taking the square root of χ^2 divided by the number of observations. Effect sizes of 0.20, 0.50, and 0.80 were interpreted as small, medium, and large effect sizes, respectively (C. J. Ferguson, 2016).

Results

Demographic Information

Descriptive data for demographic and acoustic measures are provided in Table 2. A variety of demographic information was probed to identify differences across speaker groups and sex, as well as within-group differences that were not controlled for within our models. An ANOVA investigating the effects of speaker group and sex on age indicated that there were no group differences (all ps > .549). Within persons with PD, the correlations between age and time since diagnosis (r = .06, p = .651) and age and UPDRS Part III score (r = .10, p = .404) were not significant. Additionally, a t test indicated that females and males with PD did not differ from each other based on time since diagnosis and UPDRS Part III score (both ps > .229).

Table 2. Descriptive data by participant group for demographic and acoustic variables.

Variable	With PD		Without PD	
	Female	Male	Female	Male
Age (year)	65 (7) range: 48–82	65 (7) range: 48–81	64 (7) range: 48–80	65 (7) range: 48–81
UPDRS Part III	42.60 (19.28) range: 7–97	41.94 (17.92) range: 9–77	NA	NA
Time since diagnosis (year)	6.81 (4.74) range: 1.00–18.00	5.56 (3.69) range: 1.00–16.00	NA	NA
Clinical ratings of dysarthria	25.37 (14.44) range: 6.6–59.4	30.34 (17.01) range: 4.20–66.73	15.18 (8.05) range: 1.60–35.20	14.03 (6.89) range: 4–27.4
f_o *SD* (semitones)	2.11 (0.58) range: 0.96–3.22	1.90 (0.70) range: 0.93–3.80	2.64 (0.56) range: 1.43–4.07	2.37 (0.56) range: 1.41–3.60
CPPS (decibels)	12.47 (2.01) range: 8.37–16.58	11.61 (2.06) range: 7.57–16.02	12.69 (1.71) range: 7.48–15.43	11.64 (1.65) range: 8.15–14.89
Net speech rate (syllables/s)	4.68 (0.52) range: 3.02–5.57	5.06 (0.50) range: 4.22–6.11	4.66 (0.48) range: 3.51–5.67	4.89 (0.51) range: 3.91–6.10
Percent pause ratio (%)	15.51 (7.37) range: 5.79–50.12	18.25 (5.98) range: 8.28–36.01	14.43 (3.49) range: 7.56–22.19	17.10 (4.01) range: 9.13–29.01
AAVS (Hz^2 e^4)	5.37 (1.11) range: 2.91–7.87	3.88 (1.01) range: 1.81–5.80	5.91 (1.24) range: 3.83–9.02	3.97 (0.90) range: 2.25–5.97

Note. PD = Parkinson's disease; UPDRS = Unified Parkinson's Disorder Rating Scale; NA = not applicable; f_o *SD* = fundamental frequency standard deviation; CPPS = smoothed cepstral peak prominence; AAVS = articulatory–acoustic vowel space.

Effect of Speaker Group and Sex on Continuous Measures of Speech

A multivariate analysis of variance investigating the main effects of speaker group, sex, age, and the two-way interaction of speaker group and sex on clinical ratings of dysarthria severity and acoustic measures of phonation (f_o *SD*, CPPS), speech rate (net speech rate, percent pause ratio), and articulation (AAVS) was conducted. See Supplemental Material S1 for visualizations of outcome variables. Using Pillai's trace, there were significant effects of speaker group, $F(6, 126) = 9.551$, $p < .001$, $f^2 = 0.45$; sex, $F(6, 126) = 22.587$, $p < .001$, $f^2 = 1.08$; and age, $F(6, 126) = 3.390$, $p = .004$, $f^2 = 0.16$. The two-way interaction of speaker group and sex was not significant, $F(6, 126) = 1.359$, $p = .236$, $f^2 = 0.05$. Two post hoc univariate ANOVAs were conducted to examine the main effects of speaker group and sex for each dependent variable. Speaker group had significant effects on the clinical ratings of dysarthria ($p < .001$) and f_o *SD* ($p < .001$). Persons with PD were rated as more severely dysarthric than persons without PD. This finding may be affected by the bimodal distribution of clinical ratings of dysarthria in persons with PD where 19 (30%) persons with PD received ratings more than 2 *SD*s higher than the mean ratings for persons without PD ($M = 14.60$, $SD = 7.70$). Supplemental Material S2 includes demographic and acoustic measures for this subset of persons with PD. Also, persons with PD produced smaller f_o *SD*s than persons without PD. There were no significant differences between persons with and without PD for CPPS ($p = .723$), net speech rate ($p = .286$), percent pause ratio ($p = .246$), and AAVS ($p = .185$). Speaker sex had significant effects on CPPS ($p = .003$), net speech rate ($p < .001$), percent pause ratio ($p = .004$), and AAVS ($p < .001$). Speaker sex did not have significant effects on clinical ratings of dysarthria ($p = .497$) and f_o *SD* ($p = .034$). This indicated that, on average, females had higher CPPS values, used slower net speech rates, spent less time pausing, and produced larger acoustic vowel spaces than males. Although age had a significant effect on the outcome measures, it was included as a control variable and is not to be discussed in further detail.

Effect of Speaker Group and Sex on Release Burst Precision

Four chi-square tests investigated the association between speaker group and sex on release burst precision. The frequency at which each release burst type was produced is reported in Table 3. Speaker group and sex were associated for all obligatory contexts (no burst: $\chi^2(2, N = 931) = 10.609$, $p = .001$, $\phi = 0.11$; prototypical, single burst: $\chi^2(2, N = 2{,}722) = 4.433$, $p = .035$, $\phi = 0.04$; multiple bursts: $\chi^2(2, N = 1{,}012) = 9.751$, $p = .002$, $\phi = 0.10$). As expected, persons with PD produced fewer prototypical release bursts than persons without PD. Females with PD produced the most multiple release bursts, whereas females without PD produced the most obligatory contexts with no release burst present. Speaker group and sex were not related for nonobligatory plosive contexts. More plosive contexts were identified as nonobligatory when produced by persons with PD than when produced by persons without PD, $\chi^2(1, N = 1{,}801) = 52.33$, $p > .001$, $\phi = 0.17$. Additionally, there were more nonobligatory plosive contexts produced by males than females, $\chi^2(1, N = 1{,}801) = 11.35$, $p = .001$, $\phi = 0.08$.

Discussion

A person's sex affects many factors (Cerri et al., 2019) that contribute to the higher prevalence of PD in males than in females (Picillo et al., 2017; Van Den Eeden et al., 2003) and sex differences in the clinical presentation of motor and nonmotor symptoms in PD (Haaxma et al., 2007; Kim et al., 2018; Marras & Chaudhuri, 2016). At least 70% of persons with PD experience declines in speech production (Hartelius & Svensson, 1994; Miller et al., 2007; Schalling et al., 2017), affecting phonation, speech rate, and articulation (Darley et al., 1969a; Logemann et al., 1978; Wannberg

Table 3. Chi-square test of association between speaker group and sex for release burst precision.

Release burst	Total count	With PD		Without PD		χ^2	*p*	Effect size[a]
		Female	Male	Female	Male			
Nonobligatory plosive	1,801	470 (0.47)	584 (0.40)	359 (0.67)	388 (0.57)	2.12	.146	
No burst	932	177 (2.92)	194 (3.46)	328 (1.93)	232 (2.29)	10.61	.001	0.11
Single burst	2,722	664 (1.18)	589 (1.22)	719 (1.00)	750 (1.04)	4.43	.035	0.04
Multiple bursts	1,012	303 (2.20)	247 (2.52)	209 (2.62)	253 (2.68)	9.75	.002	0.10

Note. Sum of release burst types by group and sex presented with contribution to χ^2 in parentheses. PD = Parkinson's disease.
[a]Effect sizes reported for significant *p* values.

et al., 2016). Taken together, it is critical to investigate whether changes in the speech of persons with PD are also differentially affected by a speaker's sex.

We conducted a balanced design, retrospective study of the effects of PD and sex on clinical ratings of dysarthria and acoustic measures of phonation (f_o *SD*, CPPS), speech rate (net speech rate, percent pause ratio), and articulation (AAVS, release burst precision). We found large effects of speaker group and sex, but not their interaction, and a medium effect size of age on continuous measures of speech production. Differences were found between persons with and without PD for clinical ratings of dysarthria, f_o *SD*, and release burst precision and between females and males for CPPS, net speech rate, percentage of time spent pausing, and AAVS. Only release burst precision was differentially affected by sex in persons with and without PD, but the effect size was small.

Clinical Ratings of Dysarthria

Clinical ratings of dysarthria severity are crucial for identifying perceptible changes in speech function. We collected gestalt ratings rather than domain-specific ratings, and thus, our interpretation is limited to overall speech production. Consistent with previous studies (Darley et al., 1969b; Stipancic et al., 2016, 2021; Wannberg et al., 2016), the speech-language pathologists rated speaker groups differently. Persons with PD were rated as more dysarthric than those without PD, indicating the presence of clinical changes to speech production. For this reason, our acoustic measures were likely sensitive to both subclinical and clinical changes to speech production.

A bimodal distribution was noted in the clinical ratings of persons with PD. A subset of 19 (30%) persons with PD, seven females and 12 males, were identified who had clinical ratings greater than 30.0, 2 *SD*s away from the mean clinical ratings of persons without PD. Potentially, this indicates that a third of the persons with PD included in this study presented with perceptible changes to their speech, consistent with dysarthria. When the descriptive data from the subgroup and larger group of persons with PD were compared, the measures taken from the subgroup were within 1 *SD* of the same-sex group averages reported in Table 2, except for time since diagnosis for females with PD. Thus, it is unsurprising that the subgroup of persons with PD had a f_o *SD* and percent pause ratio more than 1 *SD* away from the average of persons without PD. The greater average percent pause ratio was likely influenced by the single outlier value from a female with PD who had a percent pause ratio of 50%. Because the subgroup of persons with PD followed similar acoustic patterns as the broader group of persons with PD, it is difficult to provide a more nuanced interpretation for perceptible changes in speech production. Future studies may investigate the relationships between dysarthria severity and acoustic measures in persons with PD, potentially identifying whether this cutoff value, 30.0, is consistent across samples for distinguishing between persons with PD who do and do not have perceptual changes to speech.

More than half of our acoustic measures differed by sex, but the clinical ratings of dysarthria did not. This is unsurprising as listeners hold different expectations for a speaker based on their sex and based on these expectations, decipher what is said (Johnson, 2006). In other words, speech is perceived relative to a speaker's sex (Johnson & Sjerps, 2021). In this study, the only measure with a significant interaction between speaker group and sex was the release burst precision. The acoustic measure is based on fine-grained analysis of a single feature of plosive production. It is not clear that producing multiple release bursts affects the auditory perception of plosive consonants, but omitting a release burst may have perceptual consequences. Logemann et al. (1978) reported that persons with PD who produced errors on plosive consonants substituted fricatives for those plosives. These perceived speech errors may be related to the lack of a release burst in the acoustic signal, although we lack empirical evidence to support this claim. That being said, the rating task involved gestalt ratings of overall dysarthria and not evaluation of subdomains. Thus, it is unlikely that only plosive production errors would be perceptually salient enough to impact clinical ratings of dysarthria severity and distinguish females with PD from males with PD.

Acoustic Differences of Females and Males With and Without PD

Although speech is a motor task and there are sex differences on the presentation of motor symptoms in females and males (Haaxma et al., 2007; Kim et al., 2018), most of our results do not support our hypothesis that sex differentially affected speech symptoms in persons with PD. That being said, the majority of our measures did not differentiate between persons with and without PD. The lack of significant acoustic differences based on speaker group may reflect task-dependent effects. Task effects are consistently reported for f_o *SD* (Bowen et al., 2013; MacPherson et al., 2011), CPPS (Burk & Watts, 2019; Šimek & Rusz, 2021), speech rate (Bóna, 2014; Jacewicz et al., 2009, 2010), and vowel space measures (S. H. Ferguson & Kewley-Port, 2007; Rusz et al., 2013). Persons with PD tend to differ from persons without PD to a greater extent when generating speech than reading a standardized passage (Huber & Darling, 2011; Lowit et al., 2018). Differences in the cognitive–linguistic

demands and associated complexity of specific tasks are hypothesized to affect speech production (Altmann & Troche, 2011; Lowit et al., 2022). A standardized reading passage was chosen to allow for the comparison of speech measures across similar phonetic, syntactic, and emotional contexts, but the task may not be sufficiently demanding to elicit subtle, subclinical changes in the speech of persons with PD. Another explanation is that persons with PD were experiencing no changes or only mild speech impairments. This is possible as we were interested in persons with PD rather than persons diagnosed with hypokinetic dysarthria and 78% of our participants with PD received clinical ratings within the same range as those without PD. Finally, an alternative explanation is that the measures chosen were not sensitive to the subtle, subclinical changes in speech production that may differentiate females and males in persons with PD.

Sex differences across persons with and without PD were expected. Sex differences stem from anatomical and physiological differences between females and males across the life span (e.g., vocal fold length and f_o; Titze, 1989). Other factors, such as environment (e.g., occupational noise exposure and hearing loss; Helzner et al., 2005) and culture (e.g., language or dialect; Munson & Babel, 2019), may further contribute to sex differences in speech. Listeners accommodate these sex differences when perceiving speech (Johnson & Sjerps, 2021), but additional methods are required to account for acoustic differences in the speech of females and males. Our results identified several acoustic sex differences, replicating previous findings in persons with (Rusz et al., 2022; Whitfield & Mehta, 2019) and without (Clopper & Smiljanic, 2011; Jacewicz et al., 2009, 2010) PD. This study did not replicate previous sex differences in f_o *SD*, similar to other studies that used a semitone scale (Traunmüller & Eriksson, 1995). This supports the use of normalization techniques or transformations to nonlinear scales to account for sex differences attributable to f_o. Another way to accommodate sex differences in the acoustic signal involves using a balanced, experimental design and including sex in statistical models. Clinically, acoustic measures of speech should be compared to normative data appropriate for the person's age and sex.

Measures of Phonation

Previous research conflicted regarding the presence of an interaction between speaker group and sex on f_o *SD* (Bowen et al., 2013; MacPherson et al., 2011; Rusz et al., 2022). Our results support the lack of an interaction, consistent with the studies of Bowen et al. (2013) and Rusz et al. (2022). Unlike previous studies, this study used a large sample size and balanced design, and participants were all in the "on" phase of their levodopa/carbidopa medication. On average, persons with PD produced smaller f_o *SD*s than persons without PD. Although females tended to produce larger f_o *SD*s, this was not significant. Given the lack of a significant interaction, the results indicated that the difference in f_o *SD* between females with and without PD was similar to the difference in f_o *SD* between males with and without PD.

The second measure of phonation was CPPS, an acoustic measure related to the perception of overall severity of dysphonia (Awan et al., 2010). CPPS did not differ by speaker group, similar to previous studies that used CPPS measured from a reading passage (Burk & Watts, 2019; Šimek & Rusz, 2021). We found that females with and without PD had a higher mean CPPS value than males with and without PD, similar to the sex differences found in CPP values for sustained phonation (Rusz et al., 2022). This contradicts the idea that males produce higher CPP or CPPS values than females (Awan et al., 2012; Chen et al., 2010), but we are hesitant to speculate further because CPPS did not vary greatly in this sample. Given that our results replicate previous findings, it remains unclear whether CPPS measured from a reading passage provides clinically useful information in the evaluation of phonation for persons with PD. Only 14 (approximately 10%) participants had CPPS values below 9.33 dB, the proposed clinical cutoff for detecting dysphonia from a standardized reading passage (Murton et al., 2020), suggesting that the majority of speakers were nondysphonic. This is in contrast to previous work showing that voice quality is often affected in persons with PD (Bauer et al., 2011; Silva et al., 2012; Holmes et al., 2000; Logemann & Fisher, 1981; Midi et al., 2008). Future work is necessary to better characterize changes in voice quality in persons with PD.

Measures of Speech Rate

Both measures of speech rate were affected by sex, but not speaker group. Regardless of a PD diagnosis, we found that males produced faster net speech rates and paused for a greater percentage of the total duration of the reading passage than females. Our results only partially replicated the study of Rusz et al. (2022), who reported that there were no sex differences in the net speech rate of persons with and without PD, but that males with and without PD paused for a longer duration than females with and without PD (Rusz et al., 2022).

On average, persons with and without PD produced similar net speech rates and paused for a similar percent of time. This contradicts previous findings (Bandini et al., 2015; Huber et al., 2012; Rusz et al., 2022; Skodda, 2011), but declines in speech rate may occur later in the disease progression than other symptoms (Ho et al., 1998; Ramig, 1983). Additionally, changes in speech rate may be

obscured by baseline variation across and within speakers (e.g., sex, age, and/or speech task; Bóna, 2014; Clopper & Smiljanic, 2011; Jacewicz et al., 2009, 2010). Rather, within-speaker changes in speech rate may better capture the longitudinal effects of PD (Skodda, 2011).

Measures of Articulation

We examined two measures of articulation, the first of which related to working vowel space area. Given the previously documented sex effects on formant frequencies and various measures of vowel space (R. A. Fox & Jacewicz, 2008; Houle & Levi, 2020; Neel, 2008; Sharifzadeh et al., 2012), it is unsurprising that females had higher AAVS values than males. However, there was no effect of speaker group. One factor may be the speech task. The experimental control afforded by a reading passage may also elicit more careful productions than used for less structured tasks (Xu, 2010). Despite that, the AAVS is sensitive to vowel space–related differences between persons with and without PD, even when structured reading tasks are used (Whitfield & Goberman, 2014, 2017; Whitfield & Mehta, 2019).

The AAVS may not be sensitive to group differences if persons with PD use clear speech and persons without PD use habitual speech (Whitfield & Goberman, 2014). It is unclear whether our participants with PD produced more careful speech than participants without PD. Using careful speech is a natural strategy to improve intelligibility in many populations (S. H. Ferguson, 2012; Smiljanić & Bradlow, 2009; Stipancic et al., 2016). One caveat is that persons with PD have impairments to self-perception that affect their speech production (Clark et al., 2014; Ho et al., 2000). Additionally, we did not prompt participants to speak clearly. Taken together, it is unlikely that the majority of participants with PD were more careful in their speech production than persons without PD. A subset of 14 participants with PD, balanced by sex, had previously received speech and language therapy. Speech and language therapy for persons with PD may include explicit instruction in clear speech (Levy et al., 2020; Ramig et al., 2018; H. Shin et al., 2022). As a result, it is possible that this subgroup used strategies that had been taught to them. This seems unlikely as this subset only accounted for 22% of all of the persons with PD in the study. Additionally, seven of the seven females and four of the seven males with PD received dysarthria severity ratings greater than their respective same-sex group averages, suggesting the presence of clinical changes. Thus, it is unlikely that, on average, persons with PD were more careful in their vowel production than persons without PD.

The second measure of articulation was release burst precision, the only variable with a significant interaction between speaker group and sex. Persons with PD produced fewer plosive contexts with closure periods and subsequent aperiodic energy than persons without PD. This may indicate that persons with PD are more likely to overlap or coarticulate their phonemes. Coarticulation is a normal phenomenon but is also linked with speech rate. At faster speaking rates, speakers tend to reduce and exhibit greater overlap between phonemes (Whiteside, 1996). However, persons with PD did not use faster net speech rates than persons without PD. As we did not analyze specific phonemes beyond plosives, the degree to which phonemes overlapped is unclear. Given that persons with PD produced fewer plosive contexts than persons without PD, we assume that they had difficulties producing sufficient articulatory constrictions (Miller, 2017; Sapir, 2014) to stop airflow (visualized as the closure period), create turbulence (visualized as aperiodic energy), or both.

Persons with PD produced fewer prototypical plosives containing a single release burst than persons without PD. The pattern of nonprototypical plosives differed by speaker sex: Females with PD produced the most multiple release bursts, whereas females without PD produced the most zero release bursts. Males with and without PD produced a similar number of multiple and zero release bursts. Declines in plosive production due to PD were expected, given the results of Parveen and Goberman (2014). Contrary to our hypothesis, the release burst precision of females with PD differed from females without PD, but there was no difference between males with and without PD. One explanation is that females without PD tend to differentiate their speech sounds to a greater degree than males without PD, resulting in more precise articulation (Whiteside, 1996; Whiteside & Marshall, 2001). Although both females and males with PD may attain the same articulatory target, female release burst precision may decline to a greater degree because, initially, females without PD may hyperarticulate their productions when compared to males without PD (Whiteside, 1996). Thus, there is more room for change in the production of plosives by females with PD than for males with PD. Furthermore, the change in articulation may be observed through acoustic measurement, but speakers may still attain the same perceptual target. Further examination of release burst precision in persons with PD is warranted for replication, including exploration of factors affecting plosive production, such as place of articulation, and identification of the subsequent auditory-perceptual changes.

Clinical Implications

Speech and communication are integral to seeking and obtaining medical care. Because speech is so likely to

be impacted by PD, it is critical to identify which aspects of speech are affected in persons with PD. Additionally, the clinical presentation of PD differs for females and males, as supported by sex differences across multiple domains, including motor symptoms. As a result, we need to critically examine the role of sex on speech production, a motor task, in persons with PD. Without investigation, we are left to assume that speech production is affected similarly in females and males with PD. In other diseases, unexplored sex differences have led to delays in diagnosis, delays in treatment, and overall worse prognoses for females (e.g., cardiovascular disease; Tobb et al., 2022). This pattern applies to persons with PD: Females with PD tend to experience greater reductions to quality of life (Cerri et al., 2019) and life span (Morgan et al., 2014) than males with PD. Given that better communication quality is linked with greater use of medical services (Fawole et al., 2013), it is imperative that clinicians and researchers identify whether there are sex-specific speech declines in persons with PD. This knowledge would support the development of appropriate and responsive treatments to maintain speech and communication function. Our study provided evidence for one sex difference in persons with PD, release burst precision. Future studies should examine sex differences in consonant production and intelligibility in persons with PD.

Limitations and Future Directions

There are several limitations to this investigation, partially stemming from the retrospective design. As data collection occurred over the past 10 years and study protocols evolved over several projects, data collection methods were not consistent across participants. Specifically, the UPDRS Part II scoring, recording environments, hearing loss, and cognitive decline varied across participants. Because this information was not collected in a uniform manner, we cannot tightly control these factors. This is particularly important for the recording environments. Differences in recording environment may negatively impact acoustic measures (Bottalico et al., 2020). Given these concerns, we chose measures, f_o *SD* (Bottalico, 2017) and cepstral measures (Bottalico et al., 2020), that are relatively robust to room acoustics. Additionally, the signal-to-noise ratio met the criterion recommended by Patel et al. (2018). A standardized recording environment would allow for the examination of other acoustic measures, such as intensity, that are more sensitive to room acoustics.

Hearing loss and cognitive decline were not exclusion criteria for this study. Excluding participants based on either factor would reduce the ecological validity of our study, given age-related changes to hearing (J. Lee et al., 2012; Ries, 1994) and cognition (Ward et al., 2012). Furthermore, cognitive decline may be a symptom of PD (Cerri et al., 2019). Some of these effects may be mitigated as we included an equal number of females and males with hearing loss, although the number was not equal across speaker group. Additionally, more participants with PD experienced a cognitive decline than persons without PD, but participants were sex-matched within the groups. Despite these efforts, we could not completely control for either of these factors. Prospective work will benefit from a uniform method of data collection. This will also increase the ability to control or match participants based on not only age and sex but also hearing loss and cognitive status.

There are also limitations within the design of the study based on the inclusion of a wide range of UPDRS Part III scores for females and males with PD. The range of scores indicates that participants were in varying stages of the disease course. As a result, some participants may have presented with clinical speech changes. Our gestalt clinical ratings of dysarthria support this idea. In future work, this limitation may be reduced by setting a range criterion for UPDRS Part III scores, essentially limiting the severity of motor symptoms for a particular study group. Alternatively, subclinical changes to speech may be analyzed in persons with PD who receive similar dysarthria ratings to persons without PD.

Relatedly, this study did not account for the relationship between motor subtype and speech symptoms. Motor subtype was unable to be calculated for 14 of the 68 participants with PD (requires subitems from both UPDRS Part II and Part III) and was not balanced between females and males with PD. Given that sex differences affect acoustic measures and the recent attention to the link between motor subtype and speech symptoms in persons with PD, the greater literature will benefit from future studies including participants who are sex-, age-, and motor subtype-matched.

In the auditory-perceptual task, listeners were asked to make a single rating. Using a more refined definition of dysarthria or asking raters to make several perceptual judgments of subdomains of dysarthria would improve our ability to identify domain-specific clinical and subclinical speech deficits in females and males with PD. Although it is outside the scope of this study, future work investigating subdomains of speech ratings and their relationship with acoustic measures in persons with PD may be warranted.

An additional confounding factor is the inclusion of the subgroup of persons with PD who had previously received speech and language therapy. Persons with PD have impaired self-perception (Clark et al., 2014; Ho

et al., 2000), but speech and language therapy involves overt discussion of these speech errors and instruction in compensatory strategies to improve speech production and intelligibility (Levy et al., 2020; Ramig et al., 2018; H. Shin et al., 2022). The use of these compensatory strategies alters speech acoustics (Sapir et al., 2007), although the most well-researched therapy suggests that changes to untrained speech may be largely mitigated within 24 months after therapy (Ramig et al., 2018). Thus, future work may consider controlling for a history of speech and language therapy, possibly as an exclusion criterion or grouping factor.

Furthermore, recordings of a structured reading task were analyzed to target connected speech while maintaining experimental control over phonetic context, emotional content, and syntactic structure. This context may provide more information than sustained phonation, partly due to the need to coordinate multiple structures to produce speech, but it limits the generalizability and ecological validity of our findings. Future studies may use a combination of structured and unstructured speech tasks.

Finally, our approach for identifying pauses or silent durations may limit the generalization of the results. We constrained the pause analysis to silent durations that occurred between words and were at least 75 ms long. Although this criterion was established while referencing the average between-words pause duration of persons with and without PD, this did not control for the presence of silent durations attributable to articulatory gestures, such as a silent duration prior to a plosive consonant. If persons with PD produced articulatory gestures that were at least 75 ms in duration more frequently, it would likely result in a greater percentage of time spent pausing than persons without PD, consistent with previous literature (Goberman et al., 2005). Our analysis did not indicate any difference in the percent pause ratio between persons with and without PD, but the results may also be affected by the exclusion of intraword silent durations. Future studies should explicitly state their criterion for defining pauses, particularly with consideration to intraword silent durations that may be attributable to plosive production.

Conclusions

This study investigated the effects of sex on clinical ratings of dysarthria severity and acoustic measures of phonation, speech rate, and articulation in persons with PD. The clinical ratings of dysarthria revealed that, on average, speakers with PD were rated as more dysarthric than speakers without PD. There was considerable overlap in the distribution of ratings for persons with and without PD, indicating that our sample may include persons with PD who have subtle, subclinical speech symptoms or use compensatory strategies to mask speech symptoms. Although the acoustic measures were chosen from previous studies investigating changes in the speech of persons with PD, only f_o *SD* and release burst precision differed between persons with and without PD. Furthermore, only release burst precision was affected by the interaction of speaker group and sex, indicating that females and males with PD differed in the acoustic realization of plosive consonants. Taken together, f_o *SD* and release burst precision may be sensitive to subtle, subclinical changes or the use of compensatory strategies related to PD. Additionally, sex effects were found for all acoustic measures, except f_o *SD* measured in semitones. Acoustic measures also varied by age, although specific differences were outside the scope of this study. Taken together, the effects of sex and age on acoustic measures support that speaker characteristics impact speech production and, in turn, contribute to interspeaker variation. Overall, the current findings highlight how crucial it is to incorporate speaker sex and age when making any group comparisons between persons with and without PD or with respect to normative data.

Data Availability Statement

The data sets generated analyzed during this study are not publicly available due to the inability to fully deidentify voice recordings but are available from the corresponding author on reasonable request.

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