

Research Article

Examination of Clear Speech in Parkinson Disease Using Measures of Working Vowel Space

Jason A. Whitfield^a and Daryush D. Mehta^{b,c}

Purpose: The purpose of the current study was to characterize clear speech production for speakers with and without Parkinson disease (PD) using several measures of working vowel space computed from frequently sampled formant trajectories.

Method: The 1st 2 formant frequencies were tracked for a reading passage that was produced using habitual and clear speaking styles by 15 speakers with PD and 15 healthy control speakers. Vowel space metrics were calculated from the distribution of frequently sampled formant frequency tracks, including vowel space hull area, articulatory–acoustic vowel space, and multiple vowel space density (VSD) measures based on different percentile contours of the formant density distribution.

Results: Both speaker groups exhibited significant increases in the articulatory–acoustic vowel space and VSD₁₀, the area of the outermost (10th percentile) contour of the formant density distribution, from habitual to clear styles. These clarity-related vowel space increases

were significantly smaller for speakers with PD than controls. Both groups also exhibited a significant increase in vowel space hull area; however, this metric was not sensitive to differences in the clear speech response between groups. Relative to healthy controls, speakers with PD exhibited a significantly smaller VSD₉₀, the area of the most central (90th percentile), densely populated region of the formant space.

Conclusions: Using vowel space metrics calculated from formant traces of the reading passage, the current work suggests that speakers with PD do indeed reach the more peripheral regions of the vowel space during connected speech but spend a larger percentage of the time in more central regions of formant space than healthy speakers. Additionally, working vowel space metrics based on the distribution of formant data suggested that speakers with PD exhibited less of a clarity-related increase in formant space than controls, a trend that was not observed for perimeter-based measures of vowel space area.

Parkinson disease (PD) is a progressive neurological disorder that affects 0.3% of the general population and approximately 1% of individuals over the age of 60 years (e.g., Aarsland, Andersen, Larsen, & Lolk, 2003; De Lau & Breteler, 2006; Hirsch, Jette, Frolkis, Steeves, & Pringsheim, 2016). PD is associated with a number of motor and nonmotor deficits, but most notably, the disease leads

to a breakdown in habitual motor control caused by dysfunction of the corticobasal ganglia loops secondary to depletion of dopamine-producing cells in the midbrain (e.g., Rodriguez-Oroz et al., 2009). The cardinal motor symptoms associated with PD include rest tremor; bradykinesia, which refers to a reduction in the speed of movement initiation and progressive reduction of amplitude of motion, rigidity, or increased resistance to passive motion; and postural instability (e.g., Rodriguez-Oroz et al., 2009).

Motor control deficits associated with PD extend to the speech production system, typically resulting in hypokinetic dysarthria (e.g., Darley, Aronson, & Brown, 1969). Hypokinetic dysarthria affects phonation, articulation, prosody, and speech fluency, with the most prevalent deficits typically including reduced vocal loudness, short rushes of speech accompanied by articulatory imprecision, inappropriate silent intervals, and a reduction in the normal variation in pitch and loudness (e.g., Darley et al., 1969; Sapiro, 2014). These deficits have been quantified using

^aDepartment of Communication Sciences and Disorders, Bowling Green State University, OH

^bCenter for Laryngeal Surgery and Voice Rehabilitation, Department of Surgery, Massachusetts General Hospital, Boston

^cHarvard Medical School, Harvard University, Boston, MA

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

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acoustic measures of voice and speech. For example, several authors have reported that speakers with PD exhibit significantly lower speech and voice intensity associated with hypophonia (e.g., Dromey, Ramig, & Johnson, 1995; C. M. Fox & Ramig, 1997; Ramig, Sapir, Fox, & Countryman, 2001). Phonatory–prosodic impairment has been reflected in measures of fundamental frequency and intensity variation in connected speech (e.g., Goberman, Coelho, & Robb, 2005; Skodda, Rinsche, & Schlegel, 2009). Articulatory deficits have been documented using acoustic measures of vowel (e.g., Lam & Tjaden, 2016; Tjaden, Lam, & Wilding, 2013; Whitfield & Goberman, 2014) and consonant (e.g., Lam & Tjaden, 2016; Tjaden & Martel-Sauvageau, 2017; Whitfield, Reif, & Goberman, 2018) segments. Several investigations show that differences in acoustic measures of vowel articulation observed between speakers with PD and healthy controls reflect underlying changes in articulatory kinematics (e.g., Ackermann, Konczak, & Hertrich, 1997; Forrest, Weismer, & Turner, 1989; Mefferd, 2015; Walsh & Smith, 2012).

Vowel Space Area

Vowel space area is perhaps the most widely used acoustic measure of vowel articulation (Bradlow, Torretta, & Pisoni, 1996; Picheny, Durlach, & Braidia, 1985; Tjaden et al., 2013; Turner, Tjaden, & Weismer, 1995; Whitfield & Goberman, 2017). Vowel space metrics are calculated using the first formant (F1) and second formant (F2) frequency coordinates that are typically extracted from the midpoint of corner vowels. These measures have been used to characterize acoustic differences in vowel articulation between disordered populations and healthy controls (e.g., Hsu et al., 2017; Lansford & Liss, 2014; Tjaden et al., 2013; Turner et al., 1995; Weismer, Jeng, Laures, Kent, & Kent, 2001; Whitfield & Goberman, 2014). Additionally, vowel space metrics have been used to examine within-participant changes in articulation associated with manipulation of vocal loudness (e.g., Tjaden et al., 2013; Tjaden & Wilding, 2004; Whitfield, Dromey, & Palmer, 2018), speech rate (e.g., McRae, Tjaden, & Schoonings, 2002; Tjaden & Wilding, 2004), and speaking style (e.g., clear speech; Picheny et al., 1985; Tjaden et al., 2013; Whitfield & Goberman, 2014, 2017).

The most commonly used vowel space measures are the outlying point-based vowel space area metrics, which are calculated from the three or four corner vowels. For example, the four-point quadrilateral vowel space area (qVSA) is calculated using the F1–F2 coordinates of the corner vowels /i/, /u/, /a/, and /ae/ (e.g., Lansford & Liss, 2014; Tjaden et al., 2013; Turner et al., 1995; Whitfield & Goberman, 2017). The three-point triangular vowel space area variant is calculated from the F1–F2 coordinates from the three corner vowels /i/, /u/, and /a/ (e.g., Lansford & Liss, 2014; Skodda, Visser, & Schegel, 2011; Whitfield, Dromey, et al., 2018). Formant ratios calculated from the F1 and F2 pairs of the three corner vowels /i/, /u/, and /a/ have also been used to quantify reductions and expansions

in formant space (e.g., Lansford & Liss, 2014; Sapir, Ramig, Spielman, & Fox, 2010; Skodda et al., 2011; Tjaden, Rivera, Wilding, & Turner, 2005; Whitfield, Dromey, et al., 2018). Additionally, nonperipheral vowel space metrics, including qVSA and triangular vowel space area metrics calculated from the F1–F2 coordinates of lax vowels, have also been examined (e.g., Lam & Tjaden, 2016; Lansford & Liss, 2014; Tjaden et al., 2005, 2013).

These traditional point-based vowel space area metrics are based on F1 and F2 pairs measured at a single time point during vowel production (e.g., the vocalic midpoint or steady state), requiring that token utterance contain the target vowels. As such, prior work has estimated traditional vowel space area from single sustained vowels (e.g., Ruzs, Cmejla, Ruzickova, & Ruzicka, 2011; Ruzs et al., 2013), carrier phrases (e.g., Goberman & Elmer, 2005), and speech samples that contain the corner vowels (e.g., Ruzs et al., 2013; Whitfield & Goberman, 2017). Other authors have used average F1–F2 pairs measured from several vowel tokens across several sentences or several occurrences in a reading passage (e.g., Lam & Tjaden, 2016; Tjaden & Wilding, 2004; Turner et al., 1995).

Recent work has introduced alternative methods for quantifying formant space from continuously sampled formant frequency traces (e.g., Sandoval, Berisha, Utianski, Liss, & Spanias, 2013; Whitfield, Dromey, et al., 2018; Whitfield & Goberman, 2014, 2017). These vowel space metrics characterize formant space based on the distribution of continuous formant traces extracted from the voiced portion of connected speech, hereafter referred to as *measures of working vowel space*. Because these vowel space metrics utilize continuous formant traces, measures of working vowel space do not require stimuli that contain corner vowels to estimate vowel space area (e.g., Whitfield & Goberman, 2014, 2017). Rather, the vowel space is constructed from the data distribution of formant trajectories, not F1–F2 pairs extracted from selected vocalic nuclei of the same sentence or passage. When an utterance is short and contains a high proportion of corner vowels, measures such as the articulatory–acoustic vowel space (AAVS) are well correlated with traditional point-based measures (Whitfield & Goberman, 2017). However, when performing these measures using passage-level stimuli, a weaker relationship is expected between point-based and working vowel space metrics, as the point-based metrics only sparsely sample the full range of formant trajectories associated with production of the passage.

Examples of measures of working vowel space include the vowel space hull area (VSA_{hull}; e.g., Sandoval et al., 2013; Whitfield, Dromey, et al., 2018), the AAVS (Whitfield, Dromey, et al., 2018; Whitfield & Goberman, 2014, 2017), and vowel space density (VSD) metrics based on the density of formant data in the F1–F2 space (e.g., Story & Bunton, 2017). The VSA_{hull} is typically derived using a convex hull algorithm and thus estimates a perimeter-based vowel space area (e.g., Sandoval et al., 2013). The AAVS is equal to the square root of the generalized variance of the F1–F2 trace of an entire utterance

and represents the bivariate standard deviation of the formant data (Whitfield & Goberman, 2014). The AAVS has been shown to be sensitive to between-group and within-participant changes in vowel articulation (Whitfield & Goberman, 2014, 2017), and initial studies suggest the metric relates well to perceptual ratings of speech clarity (Whitfield & Goberman, 2017) and sentence-level metrics of lingual motion (Whitfield, Dromey, et al., 2018). VSD metrics calculate the vowel space area based on the F1–F2 data density distribution and are therefore potentially less susceptible to the effects of outlying formant data than VSA_{hull} (Story & Bunton, 2017). Additionally, VSD metrics can be calculated for different regions in the density distribution, allowing researchers to examine different regions of the vowel space (Whitfield & Goberman, 2014).

Relatively few studies have examined the utility of these recently introduced vowel space metrics for characterizing vowel space differences related to different speaker populations or speaking styles (i.e., R. A. Fox & Jacewicz, 2017; Hsu et al., 2017; Whitfield, Dromey, et al., 2018; Whitfield & Goberman, 2014, 2017). Even fewer investigations have quantified more than one working vowel space metric of a given utterance to explore differences among the AAVS, VSA_{hull} , and VSD. A study by Whitfield, Dromey, et al. (2018) calculated the AAVS and VSA_{hull} from sentences produced by healthy young adult participants and found that both were sensitive to changes in vocal loudness. However, that study did not examine relationships between the AAVS and VSA_{hull} . Because these metrics quantify different aspects of the formant distributions—specifically, variance (AAVS), perimeter-based area (VSA_{hull}), and point density (VSD)—there are likely subtle differences among these metrics. Delineating the relationships and differences among these is an important step needed for refining our approach to vowel space assessment.

Vowel Space in Speakers With PD

Studies examining formant space in the speech of individuals with PD suggest speakers with PD exhibit smaller vowel space areas than controls, potentially reflecting hypokinesia in the articulatory system (e.g., Hsu et al., 2017; Lam & Tjaden, 2016; Ruzs et al., 2013; Tjaden et al., 2013; Tjaden & Wilding, 2004; Weismer et al., 2001; Whitfield & Goberman, 2014). However, whereas several authors have reported significant differences between speakers with and without PD, others have failed to observe significant differences in vowel space area between speakers with PD and healthy controls (e.g., McRae et al., 2002; Ruzs et al., 2011; Sapir et al., 2010; Sapir, Spielman, Ramig, Story, & Fox, 2007; Weismer et al., 2001). Similarly, some studies have reported that speakers with PD exhibit smaller nonperipheral vowel space areas for lax vowels (e.g., Tjaden et al., 2013), whereas others have reported no differences (e.g., Lam & Tjaden, 2016; Tjaden et al., 2005). The tendency for speakers with PD to exhibit a smaller vowel space than control (CN) speakers likely suggests that PD is

associated with a reduction in the articulatory range of motion (e.g., Mefferd, 2015; Walsh & Smith, 2012; Weismer, Yunusova, & Bunton, 2012).

Clear Speech in Speakers With PD

Several investigations have examined the effect of slow, loud, and clear speech cues on acoustic measures of speech production in speakers with PD (e.g., Goberman & Elmer, 2005; Lam & Tjaden, 2016; McRae et al., 2002; Tjaden et al., 2013; Tjaden & Wilding, 2004; Whitfield & Goberman, 2014). In general, this work suggests that using a higher effort, goal-directed mode of speech production (e.g., clear speech, loud speech, and overenunciated speech) leads to changes in both vowel and consonant acoustics in speakers with PD (e.g., Lam & Tjaden, 2016; Tjaden et al., 2013; Whitfield & Goberman, 2014). These changes in speech production have also been associated with improvements in perceptual ratings of speech clarity and intelligibility (e.g., Tjaden, Sussman, & Wilding, 2014; Stipancic, Tjaden, & Wilding, 2016; Whitfield & Goberman, 2014). In several studies, authors report significant increases in traditional vowel quadrilateral area between habitual and clear speech variants (e.g., Lam & Tjaden, 2016; McRae et al., 2002; Tjaden et al., 2013). However, other studies have failed to observe significant changes in vowel quadrilateral area from habitual to clear speech styles for speakers with PD (e.g., Goberman & Elmer, 2005).

Several factors may contribute to the inconsistent performance of traditional vowel space area metrics to detect statistical differences between groups. First, the speakers with PD are a relatively heterogeneous population, and factors such as disease stage, dysarthria characteristics, and speech symptom severity likely influence the extent to which vowel space area is affected (e.g., Goberman & Elmer, 2005; Lam & Tjaden, 2016; Tjaden et al., 2013). Additionally, the speaking task from which formant frequency pairs are extracted has been shown to affect vowel space area (e.g., Kuo & Weismer, 2016; Ruzs et al., 2013). For example, Ruzs et al. (2011) failed to observe differences in vowel space area measured from a vowel prolongation task between speakers with and without PD. In a follow-up study, the authors found that vowel space area differed between speakers with and without PD when measured in a sentence reading and monologue task, but not for the vowel prolongation task (Ruzs et al., 2013). In a study of healthy controls, Kuo and Weismer (2016) found systematic F1–F2 centralization (i.e., vowel space area reduction) across speaking tasks. In that study, carrier phrase repetition, reading, and conversational speech each yielded significantly greater vowel reduction compared to target vowel production in an /hVd/ context using clear speech (Kuo & Weismer, 2016). Additionally, work by Tjaden et al. clearly documents that the type of instruction has a direct impact on the magnitude of the clear speech response (e.g., Lam & Tjaden, 2016; Lam, Tjaden, & Wilding, 2012; Tjaden et al., 2013, 2014; Stipancic et al.,

2016), potentially explaining some of the discrepancies in the clear speech response reported between studies.

In addition to these factors, it is possible that traditional vowel space metrics lack sensitivity to subtle within- and between-participant differences in vowel articulation (e.g., Sapir et al., 2010; Whitfield, Dromey, et al., 2018; Whitfield & Goberman, 2014, 2017). For example, Sapir et al. (2010) suggest that quadrilateral and triangular vowel spaces are highly sensitive to interspeaker variability, which may mask statistical differences between speaker groups or speaking styles. Data from Whitfield, Dromey, et al. (2018) suggest that working vowel space metrics, such as the AAVS and VSA_{hull} , that reflect dynamic aspects of vowel articulation associated with vowels and consonants better capture within-speaker differences in articulation than point-based metrics, such as the triangular vowel space area and vowel articulation index. In studies of healthy speakers, both vowel triangular and quadrilateral area metrics have failed to capture within-participant changes in vowel articulation associated with speaking louder (e.g., Whitfield, Dromey, et al., 2018) and more clearly (e.g., Whitfield & Goberman, 2017) than usual. In these same studies, significant increases in the AAVS were observed for the same utterances with loud (Whitfield, Dromey, et al., 2018) and clear (Whitfield & Goberman, 2017) speech. Therefore, the inconsistent performance of traditional vowel space area metrics may be related to an undersampling of the full range of articulatory-acoustic behavior, as these metrics are calculated from only three or four points in F1–F2 space (Whitfield, Dromey, et al., 2018; Whitfield & Goberman, 2014, 2017).

Although few in number, initial reports using these working vowel space metrics that capture the full formant trace have observed smaller vowel space areas in speakers with PD compared to CN speakers (Hsu et al., 2017; Whitfield & Goberman, 2014). Hsu et al. (2017) found that VSA_{hull} calculated from formant traces of a reading passage was smaller for Mandarin speakers with PD compared to neurologically healthy controls. In another study, Whitfield and Goberman (2014) observed significant clarity-related increases in the AAVS calculated from the formant trace of the first sentence of the Rainbow Passage produced by speakers with PD. A prior investigation of the same speaker group reported no clarity-related change in traditional vowel quadrilateral area measured from a carrier phrase (Goberman & Elmer, 2005). It is therefore possible that traditional vowel space metrics undersample the full range of the formant space and do not capture subtle differences in the formant space between groups and within talkers. Thus, further exploration of working vowel space metrics that have demonstrated preliminary success in detecting subtle differences in vowel articulation associated with speech production in individuals with PD is warranted.

Purpose

In summary, prior work examining clear speech production in speakers with PD has primarily utilized traditional vowel space metrics that may not sensitively capture

subtle differences in articulation associated with hypokinetic dysarthria and speech style manipulation. Initial studies demonstrate that working vowel space metrics capture differences between speakers with PD and healthy controls (e.g., Hsu et al., 2017; Whitfield & Goberman, 2014). Additionally, only one study to date has examined clear speech behavior in individuals with PD using a vowel space metric based on frequently sampled formant trajectories (i.e., Whitfield & Goberman, 2014). That study, however, was limited to one sentence, which may not represent the full range of articulatory behavior over a speaking task. Therefore, the aim of the current investigation was to characterize differences in clear speech production between speakers with and without PD using several working vowel space metrics calculated from formant frequency traces of a reading passage. This preliminary work explores the extent to which different working vowel space metrics capture differences between speakers with and without PD, as well as within-speaker changes in vowel articulation associated with clear speech. This study, therefore, was an initial evaluation of the relative utility of these working vowel space metrics for capturing differences in formant space between speakers with and without PD when using clear speech. Additionally, the strength of the relationships between each vowel space metric was quantified to better describe the extent to which these metrics characterize different or redundant aspects of formant space. A more complete characterization and examination of these recently introduced vowel space metrics may help guide measure selection in future research.

Method

Fifteen individuals with PD (11 men, four women) and 15 neurologically healthy CN participants (seven men, eight women) completed the informed consent process and served as speakers for the current study. The mean age of the individuals in the older adult CN group was 66.47 years ($SD = 7.06$), whereas the mean age of speakers in the PD group was 65.87 years ($SD = 6.76$). An independent-samples *t* test confirmed that there was no significant difference in age between the CN group and the PD group, $p > .05$. For speakers in the PD group, the mean time since diagnosis was 7.59 years (range: 11 months to 25 years). All individuals in the PD group had received a diagnosis of idiopathic PD from a neurologist trained in movement disorders and were undergoing pharmacological treatment for the symptomatic management of PD. At the time of completing the speech tasks for the current study, all participants in the PD group reported that they were in the “on” medication state. For all but one participant with PD, Part III of the Unified Parkinson’s Disease Rating Scale (UPDRS) was administered by a trained researcher to characterize motor symptom severity on the day of the recording. The Hoehn and Yahr stage was used to characterize disease progression. The UPDRS and Hoehn and Yahr stage could not be measured for one participant (PD15) because the researcher trained in the administration

of the UPDRS was not available on the day of data collection. All participants reported being in the “on” medication state at the time of the recording. Disease-related information for each participant in the PD group is reported in Table 1.

All participants completed a series of screenings before completing the speech tasks for the current study. Hearing was screened using a calibrated MAICO MA25 audiometer at 500, 1000, 2000, and 4000 Hz. Participants over the age of 65 years were screened at 40 dB, whereas participants under 65 years of age were screened at 25 dB, as per the protocols outlined by Roeser and Clark (2007). All participants in the current study passed a hearing screening or were wearing hearing aids that were prescribed by an audiologist. The Dementia Rating Scale–2 (Mattis, 2004) was administered by a clinical fellow in speech-language pathology. All participants passed the screening, with all scores above 134 (range: 144–134), which is well above the cutoff score of 123 that indicates mild cognitive impairment (e.g., Petersen et al., 1999). Finally, a motor speech assessment was completed using recorded audio. For this assessment, participants prolonged the vowel /a/, performed alternating and sequential motion rates, and read the Rainbow Passage at a comfortable rate and loudness. Dysarthria type and severity were determined by identifying and rating the severity of the deviant speech characteristics according to the assessment protocols outlined in Mayo Clinic studies (e.g., Darley et al., 1969). Results from the assessment suggested all participants exhibited hypokinetic dysarthria that ranged in severity from mild to moderate–severe (see Table 1).

Protocol

For the current study, participants were asked to read a carrier phrase and the Caterpillar Passage (Patel et al., 2013) at a habitual pitch, loudness, and speaking rate, as if they were talking to someone seated across the table. The

carrier phrase was “Say hVd again,” which was repeated for each of the four corner vowels in American English: V = /i/, /a/, /æ/, and /u/. The data from the carrier phrase were included in the current study to include a traditional point-based vowel space measure. After reading the phrases and passage in the habitual condition, participants were then asked to read the phrases and passage again “as clearly as possible, as if someone seated across the table was having trouble hearing or understanding you.” The speech samples were recorded in a quiet room using a tabletop microphone (Shure SM-58) at a constant mouth-to-microphone distance of 30 cm onto a digital recorder (Marantz PMD661; sampling rate = 44.1 kHz).

Acoustic Analyses

Speech Rate, Pause Metrics, and Point-Based Vowel Space Area

Measures of speech timing were examined for each reading sample because clear speech production often elicits changes in speech rate and pause, which may affect other characteristics of the speech signal including vowel space. To measure temporal changes in speech production, mean articulation rate, mean pause duration, and pause-to-speech ratio were measured for each passage using PRAAT. A spoken interval was defined as an interval of sounded speech in the acoustic signal bounded by at least 150 ms of silence. First, all silent and spoken intervals in the acoustic signal were identified using a custom pause detection PRAAT script. The intervals were then manually adjusted to ensure the accuracy of the segmentation using the waveform and spectrogram as a visual guide. The number of syllables produced during each spoken interval was manually recorded in the interval tier. The articulation rate of each spoken interval was calculated by dividing the syllable count by the interval duration, and the mean articulation rate was computed over all spoken intervals within each passage. The mean pause duration was calculated by

Table 1. Participant descriptors for the Parkinson disease (PD) group.

Participant	Sex	Age (years)	Years since PD diagnosis	UPDRS	H&Y stage	Dysarthria severity
PD01	M	66	10	36	2	Moderate
PD02	M	71	5	36	2.5	Moderate
PD03	M	53	7	35	1.5	Moderate
PD04	M	65	9	57	2	Moderate to severe
PD05	M	46	25	29	2.5	Moderate
PD06	M	76	5	34	1.5	Mild
PD07	F	57	5	20	2	Moderate
PD08	F	63	2	37	3	Mild to moderate
PD09	M	62	0.9	35	1.5	Mild
PD10	M	74	11	55	3	Severe
PD11	F	60	2	48	3	Mild
PD12	F	77	9	56	3	Moderate
PD13	M	67	6	27	2	Mild
PD14	M	69	11	22	2	Mild to moderate
PD15	M	64	6	—	—	Moderate to severe

Note. Columns include sex (M = male; F = female), age (years), Unified Parkinson’s Disease Rating Scale (UPDRS), Hoehn and Yahr (H&Y) stage, and hypokinetic dysarthria severity rating.

averaging the durations of the silent intervals. Pause-to-speech ratio was calculated as the sum of the silent interval durations divided by the sum of the spoken interval durations. Similar analyses have been used to examine speech and pause timing (e.g., Tjaden & Wilding, 2011).

In addition to measures of articulation rate and pause, a traditional point-based vowel space metric was computed from the midpoint formant frequencies of the four corner vowels embedded within the carrier phrase. PRAAT was used to manually obtain the F1 and F2 values from the midpoint of the corner vowels produced using habitual and clear speech styles (e.g., Goberman & Elmer, 2005; Whitfield & Goberman, 2017). The F1–F2 pairs were computed at the midpoint of the steady state of vowel production, before the formant transition associated with the final voiced alveolar stop. The steady state was operationally defined using the spectrographic display as a guide and included the interval over which there was the least change in the F1–F2 pattern (e.g., Fletcher, McAuliffe, Lansford, & Liss, 2017). For productions for where there was no steady state in the formant pattern, the F1–F2 pair was computed at the vocalic midpoint (e.g., Lansford & Liss, 2014). Twenty percent of the data were reanalyzed to assess reliability of the method, and intrarater analysis revealed that all the formant frequency values were within 3% of the original value. The qVSA was computed from the F1–F2 pairs of the four corner vowels using the formula of an irregular quadrilateral reported by Kent and Kim (2003), $qVSA = |0.5 \times |F2/i/ \times F1/ae/ + F2/ae/ \times F1/\alpha/ + F2/\alpha/ \times F1/u/ + F2/u/ \times F1/i/ - F1/i/ \times nF2/ae/ + F1/ae/ \times F2/\alpha/ + nF1/\alpha/ \times F2/u/ + F1/u/ \times F2/i/|$.

Working Vowel Space Metrics

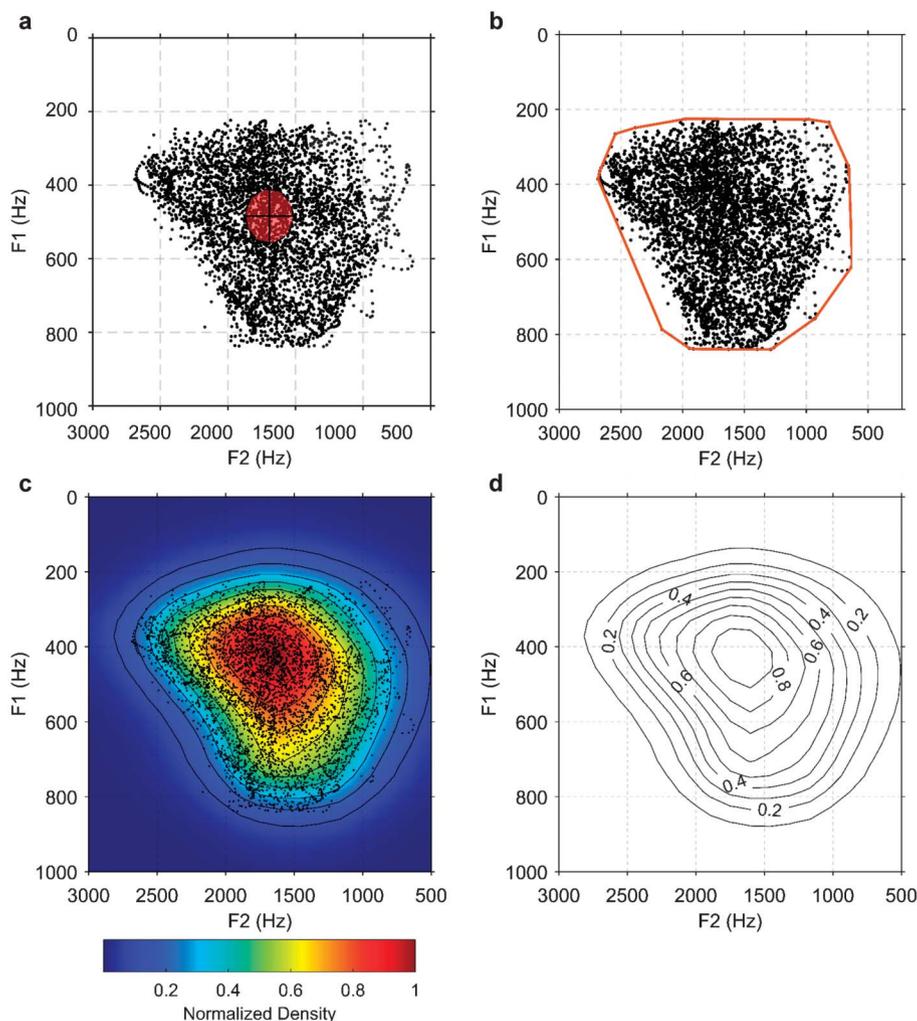
Time series of the first three formant frequencies were extracted using a Kalman-based autoregressive approach consisting of three stages: preprocessing, intraframe observations, and interframe tracking (Mehta, Rudoy, & Wolfe, 2012). This approach has been used in several studies to extract continuous formant traces from connected and conversational speech (e.g., Horwitz-Martin et al., 2016; Williamson et al., 2015). During the preprocessing, the acoustic waveform was resampled to 7000 Hz to track three formants within a 3500-Hz bandwidth, the resampled waveform was segmented into 20-ms Hamming window frames with 50% overlap, and each frame was filtered using a first-order difference equation with a preemphasis coefficient of 0.95. During the intraframe observation stage, each frame was modeled as a stochastic autoregressive process with 12 linear predictive coding coefficients that were transformed to 15 cepstral coefficients. Finally, interframe tracking was accomplished by deriving the first three formant frequencies as a linearized mapping of the cepstral coefficients, which were observations in a state-space framework that was solved using an extended Kalman smoother. The applied formant tracker provided well-behaved time series that smoothly coasted through non-speech frames.

After formant extraction, the formant frequencies were processed and filtered using a custom MATLAB script. The F1–F2 pairs, along with the corresponding time stamps, were imported into MATLAB. The PRAAT-based PointProcess function was used to identify voice and voiceless intervals in each speech sample. Voiced frames were identified when the fundamental frequency was reported by PRAAT, and consecutive voiced frames were defined as voiced intervals (maximum period = 20 ms). Voiced interval boundaries were imported into MATLAB to ensure that formant trajectories from the voiced portion were analyzed. For each voiced interval, the local outliers in the formant trace were removed using a median absolute deviation moving average function in MATLAB. The formant trace was then low-pass filtered at 10 Hz. As a final step, bivariate outliers in the filtered formant trajectory were identified by calculating the Mahalanobis distance for each F1–F2 pair. F1–F2 pairs that were greater than 2 *SDs* from the centroid were removed from the trace.

Prior work suggests that the phonetic content of the spoken utterance affects working vowel space metrics, such as the AAVS and VSA_{hull} (e.g., Whitfield, Dromey, et al., 2018; Whitfield & Goberman, 2017). However, given a sufficiently long and phonetically balanced speech sample, formant data are expected to saturate the F1–F2 space, leading to convergence of these passage level metrics. A recent study conducted using formant data extracted from the Caterpillar Passage revealed that the AAVS typically converges to a stable value within the first half of the passage (Whitfield, Gravelin, Kriegel, & Mehta, 2018). Cumulative AAVS estimates were calculated by iteratively adding F1–F2 pairs from successive voiced frames. Power functions that compared the absolute percent difference between each AAVS estimate and the AAVS passage value were examined. Within the first half of the reading passage, the AAVS converged to a value that was within 5% of the passage value for all speakers (Whitfield, Gravelin, et al., 2018). These data suggest that the speech samples examined in the current study were of sufficient length to accurately quantify metrics of working formant space.

For the current investigation, several summary vowel space metrics were calculated from the F1–F2 formant trajectory plot extracted from the entire Caterpillar Passage. First, the AAVS was calculated as the square root of the generalized variance of the F1–F2 formant data (Whitfield, Dromey, et al., 2018; Whitfield & Goberman, 2014, 2017). The generalized variance calculation is equal to the bivariate variance of the F1–F2 data and is calculated as the product of the F1 variance and F2 variance and the proportion of the variance that is not attributed to the relationship between F1 and F2. Therefore, the AAVS represents the mean variation or working area around the F1–F2 distribution of the entire passage. The acoustic vowel space area hull (VSA_{hull}) was calculated using the convex hull algorithm in MATLAB (e.g., Whitfield, Dromey, et al., 2018). Figure 1 provides a visual representation

Figure 1. Visual representations of measures of working formant space computed from the Caterpillar Passage spoken by a healthy speaker in the habitual condition: (a) articulatory–acoustic vowel space, (b) vowel space hull area, and (c) vowel space density metrics, which are quantified as the area of the (d) different density contours in the formant space. F1 = first formant; F2 = second formant.



of the AAVS, VSA_{hull} , and VSD metrics computed from the Caterpillar Passage spoken by a CN participant in the habitual condition.

In addition to the AAVS and VSA_{hull} metrics, vowel space area metrics based on the density distribution of the formant data in F1–F2 space were also calculated. These vowel space area metrics will be hereafter referred to as *VSD* (e.g., Story & Bunton, 2017) and are also depicted in Figure 1. The VSD metrics were calculated using a custom MATLAB script, which calculated the relative density for the formant data in F1–F2 space. For each sample, the bounds of the F1–F2 mesh extend from 0 Hz to 1.5 times the median F1 and F2 value in the passage-length data distribution. This space was then divided into a 30×30 grid. The number of F1–F2 pairs in each grid was tallied to approximate the density distribution. A local smoothing function was used to smooth the density distribution in

both dimensions, smoothing over one bin around a given point (see Eilers & Goeman, 2004, for the MATLAB function). The density distribution was then normalized by dividing the counts by the largest number of F1–F2 pairs in a given bin. Figure 1c shows the smoothed normalized density distribution. The area of the smoothed density contours was then extracted using the polyarea function in MATLAB. VSD metrics were extracted using nine criteria, ranging from 10% to 90% of the normalized density. For the current study, the naming convention used to notate the VSD metrics includes the density criterion (i.e., VSD_{10} , VSD_{20} , VSD_{30} , VSD_{40} , VSD_{50} , VSD_{60} , VSD_{70} , VSD_{80} , and VSD_{90}). For example, VSD_{10} represents the VSD measures that represent the area of the 0.1 (10%) density contour, whereas VSD_{90} represents the area of the 0.9 density contour located in the centermost region of the VSD plot (see Figure 1d for an example of density contours).

Statistics

Descriptive statistics for the vowel space, articulation rate, and pause metrics were calculated for each group and speaking style. To ensure that both speaker groups exhibited the expected changes in speech production associated with clear speech, four initial linear mixed-effects models (LMMs) were constructed using articulation rate, pause-to-speech ratio, pause duration, and the point-based qVSA as the dependent variables. For the articulation rate and pause measures, fixed effects included group, style, and the Group \times Style interaction. For the point-based qVSA, fixed effects included group, style, and sex, as well as the Group \times Style interaction effect. Sex was included as a fixed factor to account for sex-related differences in qVSA related to differences in vocal tract size between male and female speakers. For all models, participant was modeled as a random intercept term to account for repeated measurement.

For the primary analyses, four LMMs were constructed using the AAVS, VSA_{hull} , VSD_{10} , and VSD_{90} as the dependent variables. Descriptive statistics for the other VSD metrics were reported but not subjected to statistical analysis to limit the number of statistical comparisons. The VSD_{10} and VSD_{90} were chosen for the statistical analyses because they quantified the most peripheral (i.e., VSD_{10}) and most central (i.e., VSD_{90}) regions of the formant density distribution. For each of the LMMs, fixed effects included main effects of group, style, and sex, as well as the Group \times Style interaction effect. Participant was modeled as a random intercept. For all LMMs, the intercept was mapped to the CN group in the habitual speech style. To examine changes from the habitual to clear speech style for the PD group, these models were relevelled by mapping the PD group to the intercept. Sex coded centered around zero with male coded as -0.5 and female coded as 0.5 .

As prior work has not examined the relationships among the various vowel space metrics, univariate regression analyses were performed and coefficients of determination (R^2) values were calculated to quantify the strength of the relationship between each vowel space metric. All statistical analyses were performed in R using the lmer and lmerTest packages. Standard data screening procedures were conducted before executing the statistical test to ensure valid interpretation of the statistical output. Because the primary goal of the study focused on four main working vowel space metrics, alpha was corrected using a Bonferroni adjustment ($.05 / 4$) and the criterion of 0.0125 was used for all significance testing.

Results

Articulation Rate, Pause Measures, and Point-Based Vowel Space Area

Figure 2 displays speech rate measures for the habitual and clear speech styles in terms of mean articulation rate, mean pause duration, and pause-to-speech ratio.

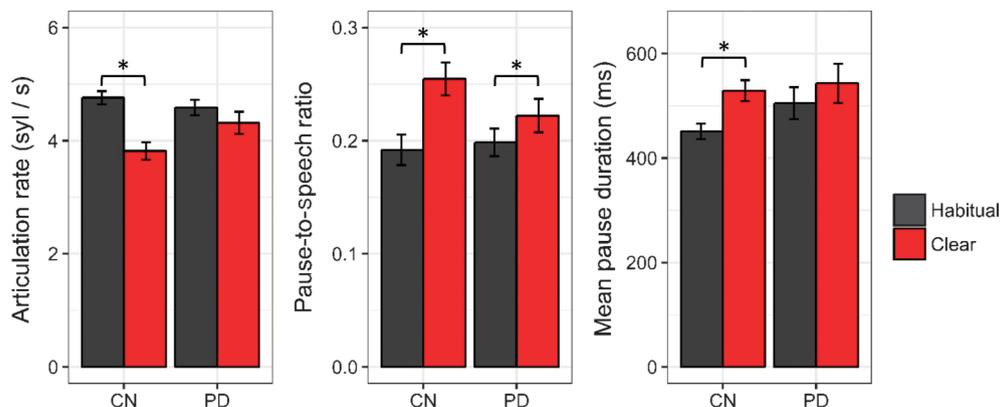
Statistical analysis revealed a main effect of speaking style for mean articulation rate, $F(1, 30) = 35.106, p < .001$; mean pause duration, $F(1, 30) = 24.669, p < .001$; and pause-to-speech ratio, $F(1, 30) = 23.424, p < .001$. On average, speakers exhibited longer mean pause durations and a higher pause-to-speech ratio for the clear style compared to the habitual style. Main effects of group were not observed for rate or pause measures, $p > .0125$. These effects were qualified by a significant Group \times Style interaction that was observed for articulation rate, $F(1, 30) = 10.680, p = .003$. Parameter estimates revealed that the decrease in articulation rate from the habitual to clear style was significantly less for speakers with PD than controls, $b = 0.675$ syllables per second, $SE = 0.205, t(30) = 3.295, p = .003$. Whereas CN speakers exhibited a statistically significant decrease in articulation rate from habitual to clear style, $b = -0.944$ syllables per second, $SE = 0.145, t(30) = -6.520, p < .001$. Releveling the model revealed that speakers with PD exhibited a slight reduction in articulation rate from habitual to clear speech that was not statistically significant, $b = -0.222$ syllables per second, $SE = 0.143, t(29) = -1.557, p = .13$. Therefore, both speaker groups exhibited an increase in the proportion of pause and mean pause duration from the habitual to clear speech style. Additionally, only CN speakers exhibited a significant slowing of articulation rate from the habitual to clear speech style, whereas speakers with PD exhibited no change in articulation rate between speech styles.

Point-based vowel space area was calculated from the formant frequency pairs extracted from corner vowel nuclei contained within a carrier phrase using habitual and clear speech styles. Results for qVSA revealed that a significant effect of speaking style, $F(29.02, 1) = 39.480, p < .001$, and sex, $F(29.02, 1) = 62.293, p < .001$. The main effect of group was not statistically significant, $p = .160$, nor was the Group \times Style interaction, $p = .637$. Parameter estimates revealed that qVSA significantly increased from the habitual to clear speech style for all speakers, $b = 106157.0$ Hz, $SE = 21823.0, t(29.02) = 4.87, p < .0001$, and that qVSAs were larger for females than males, $b = 224450.0$ Hz, $SE = 28438.0, t(29.00) = 7.89, p < .0001$.

Working Vowel Space Metrics

Table 2 shows the means and standard deviations of the traditional point-based vowel space area (qVSA) and working vowel space metrics (AAVS, VSA_{hull} , and the nine VSD measures) for both groups in habitual and clear conditions. Figure 3 shows sample visual representations of the AAVS, VSA_{hull} , VSD_{10} , and VSD_{90} metrics for the habitual and clear speech styles for one CN participant and one participant with PD. Note that the formant data are not displayed as in Figure 1 because each plot includes a visual representation of the formant area measure for the habitual and clear speech styles. LMM analyses were conducted for the AAVS and VSA_{hull} metrics to examine the main effects of group, speaking style, and sex, as well

Figure 2. Means and standard error for articulation rate, pause-to-speech ratio, and mean pause duration for the control (CN) group and Parkinson disease (PD) group in the habitual (black) and clear (red) speech styles.



as the Group \times Style interaction. Figure 4 shows the mean and standard error for the four vowel space metrics that were examined in the statistical analyses.

AAVS

The LMM for the AAVS revealed main effects of sex, $F(30, 1) = 9.001$, $p = .005$, and style, $F(30, 1) = 92.195$, $p < .0001$, and a significant Group \times Style interaction, $F(30, 1) = 10.936$, $p = .0025$. Although speakers with PD exhibited a smaller AAVS, on average, than the CN participants, the main effect of group did not reach statistical significance, $p = .08$. Table 3 shows the parameter estimates for the LMM. The analysis revealed that female talkers exhibited an AAVS that was 11776.9 Hz², $SE = 3925.4$, larger than exhibited by male talkers. A significant AAVS increase of 12147.8 Hz², $SE = 1330.8$, was observed

from the habitual to clear speech style for CN speakers. Further testing confirmed that both groups exhibited a significant increase in the AAVS between the habitual and clear styles, $p < .0001$ for both comparisons. However, the clarity-related increase in the AAVS was significantly less for speakers with PD than controls, $p = .0025$. Speakers in the CN group exhibited a 26.16% increase in the AAVS from the habitual to clear condition ($SD = 14.12$, range: 8.33%–49.41%), whereas the percent increase for speakers with PD was 14.95 ($SD = 9.31$, range: 4.99%–31.81%).

VSA_{hull}

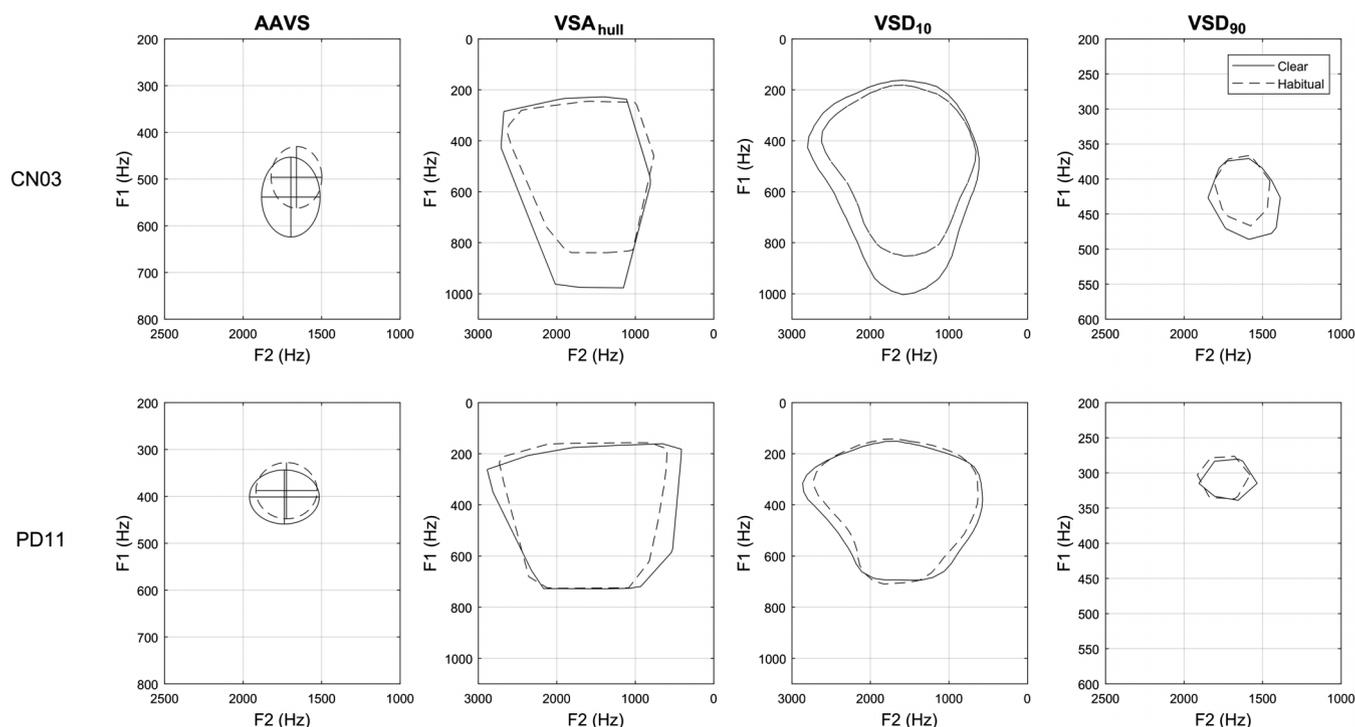
The LMM for VSA_{hull} revealed only a main effect of style, $F(1, 29.99) = 37.919$, $p < .0001$. As shown in the parameter estimates (see Table 3), all other effects did not reach statistical significance. A statistically significant

Table 2. Mean (standard deviation) of the vowel space metrics examined for the habitual and clear speech styles for speakers with Parkinson disease and healthy controls.

Metric	Control group				Parkinson disease group			
	Habitual		Clear		Habitual		Clear	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
qVSA	398151.3	108305.7	504308.6	148589.0	309613.9	134247.1	400805.2	168505.7
AAVS	46745.2	8944.8	58893.0	12191.5	39901.4	12576.0	45825.2	14629.2
VSA _{hull}	988912.1	217751.1	1154317.6	211213.4	881280.4	242166.4	992559.3	257661.0
VSD ₁₀	814152.4	140391.5	978001.4	161576.6	680879.1	176122.3	773903.4	206007.0
VSD ₂₀	597442.0	120648.4	734289.8	130924.8	480548.4	140720.3	564761.2	167643.5
VSD ₃₀	448969.9	107914.7	523449.4	173755.2	358500.3	112560.3	426432.7	138802.3
VSD ₄₀	315324.3	127336.1	350616.7	166944.6	265096.9	87557.5	294987.7	141165.2
VSD ₅₀	246042.3	82104.5	250099.1	118668.2	189310.6	68427.8	230585.3	97378.8
VSD ₆₀	167202.0	56818.0	197183.6	70242.2	131766.0	52737.2	152019.7	72729.5
VSD ₇₀	111231.2	41292.4	125597.4	41232.8	84763.5	34981.6	101794.7	50035.4
VSD ₈₀	65333.6	27602.2	70579.8	24820.1	48540.5	21028.8	58519.2	30493.4
VSD ₉₀	29404.7	13443.7	30107.2	10856.8	20845.6	9120.7	23864.1	10810.1

Note. All metrics are expressed in square hertz. qVSA = quadrilateral vowel space area; AAVS = articulatory–acoustic vowel space; VSA_{hull} = vowel space hull area; VSD = vowel space density metrics, calculated as the area of the various density contours in the formant density distribution.

Figure 3. Example visual representation of the articulatory–acoustic vowel space (AAVS), vowel space hull area (VSA_{hull}), vowel space density (VSD) metrics, VSD_{10} , and VSD_{90} for habitual (dashed lines) and clear (solid lines) productions by a participant in the control group (CN03; top panels) and PD group (PD11; bottom panels). Note that the AAVS and VSD_{90} scales differ from the VSA hull and VSD_{10} plots but that the scales are consistent for each measure to allow for between-participants comparisons. The horizontal and vertical lines within the AAVS ellipse show the standard deviation of the second formant (F2) and first formant (F1) data, respectively. Individual formant data were excluded from the plot for clarity because each panel includes measures from both the habitual and clear styles.



increase in VSA_{hull} was observed between the habitual and clear styles, $p < .0001$. Post hoc testing confirmed that both speakers with and without PD exhibited a significant increase in VSA_{hull} between the habitual and clear styles, $p < .01$ for both comparisons. The percent change in VSA_{hull} was 18.24 for the CN group ($SD = 12.89$, range: -5.24% to 36.04%) and 11.75 for the PD group ($SD = 6.61$, range: -2.88% to 53.22%). Figure 4 shows the means and standard errors for the AAVS and VSA_{hull} vowel space metrics, indicating significant contrasts.

VSD-Based Metrics

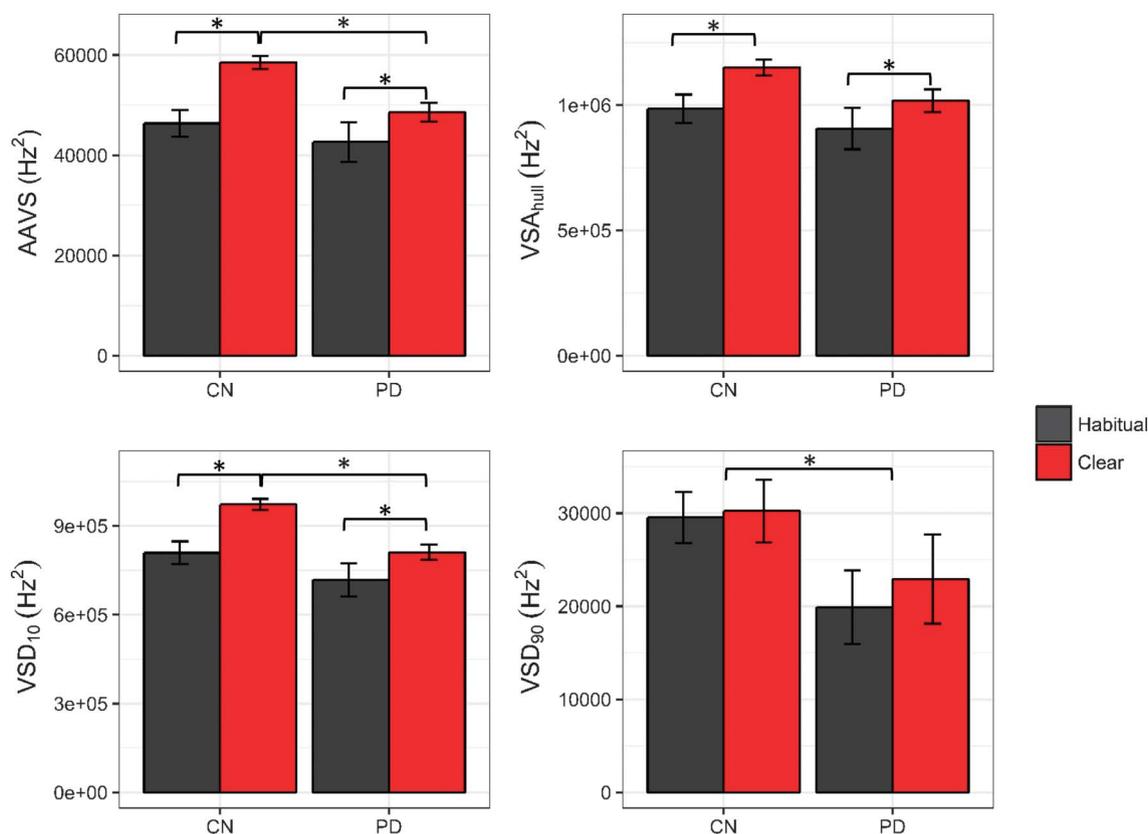
LMM analyses were performed for VSD_{10} and VSD_{90} , which were the areas calculated using the 10% and 90% criteria and represent the most peripheral and central layers of the formant density distribution, respectively. For the peripheral VSD_{10} , statistically significant main effects were observed for sex, $F(30, 1) = 7.843$, $p = .0085$, and style, $F(30, 1) = 113.767$, $p < .0001$, as well as a significant Group \times Style interaction, $F(30, 1) = 8.927$, $p = .0063$. The average difference in VSD_{10} between males and females was $158,152.3 \text{ Hz}^2$, $SE = 56,140.8$, with female talkers having a large VSD_{10} than males. Parameter estimates, which are reported in Table 3, revealed that the slightly

lower VSD_{10} for speakers in the PD group compared to controls was not statistically significant, $p = .1508$. The CN group exhibited a significant increase in VSD_{10} from the habitual to clear speech style, $p < .0001$. Similar to the AAVS, speakers with PD exhibited significantly less clarity-related increase in the VSD_{10} than controls, $p = .0056$. As with the AAVS, both speaker groups exhibited a significant increase in the VSD between the habitual and clear styles, $p < .0001$ for both comparisons. Additionally, there was a significant difference in VSD_{10} between groups for the clear, $p = .0082$, but not the habitual, $p = .0405$, condition. The percent change in VSD_{10} was 18.27 for speakers in the CN group ($SD = 9.59$, range: 5.05% – 38.28%) and 11.75 for speakers in the PD group ($SD = 6.61$, range: 3.98% – 23.65%). For the more central region of the vowel space measured by VSD_{90} , the model revealed main effects of style, $F(30, 1) = 11.273$, $p = .0023$, and group, $F(30, 1) = 7.147$, $p = .0120$. The main effects of sex and Group \times Style interaction were not statistically significant, $p > .0125$.

Relationships Among Vowel Space Metrics

As a preliminary examination of the relationships among the different vowel space metrics, univariate

Figure 4. Means and standard error for the articulatory–acoustic vowel space (AAVS), vowel space hull area (VSA_{hull}), and vowel space density metrics (VSD_{10} and VSD_{90}) for the control (CN) group and Parkinson disease (PD) group in the habitual (black) and clear (red) speech styles. * $p < .01$.



regression analyses were performed to compute the coefficient of determination (r^2) between each vowel space metric. As expected, the relationship between the working AAVS and VSA_{hull} was relatively strong, $r^2 = .81$. Figure 5 plots the pairwise R^2 values between the nine VSD metrics and the AAVS and VSA_{hull} . As shown in Figure 5, the strength of the relationship between the VSD metrics and the AAVS and VSA_{hull} decreases as VSD metrics reflect the area of denser, more centralized regions of the formant space. The relationship between the AAVS and VSD_{10} was strong ($r^2 = .94$), whereas the relationship between the VSA_{hull} and VSD_{10} was moderate to strong ($r^2 = .69$). The relationship between the AAVS and VSD_{90} was much weaker ($r^2 = .20$), as was the relationship between the VSA_{hull} and VSD_{90} ($r^2 = .12$).

The relationship between the traditional, point-based qVSA and the working metrics was relatively weak in comparison to the strength of the relationships among the passage level metrics. The relationship between the working AAVS and qVSA was moderately strong ($r^2 = .55$), whereas the relationship between the VSA_{hull} and the qVSA was weak to moderate ($r^2 = .32$). As shown in Figure 5, the relationship between the qVSA and VSD metrics also decreased, as the VSD

metrics reflected the area of denser regions of formant space: qVSA versus VSD_{10} ($r^2 = .49$) and qVSA versus VSD_{90} ($r^2 = .001$).

Discussion

The current investigation examined the effect of clear speech on several vowel space metrics that were calculated from time-varying formant trajectories extracted from paragraph-length stimuli spoken by individuals with and without PD. Speakers with PD and CN talkers produced the Caterpillar Passage (Patel et al., 2013) using both habitual and clear speech styles. As expected, most vowel space metrics exhibited a significant increase between the habitual and clear speech styles. Comparable changes in the speaking rate metrics were also observed. Both groups exhibited an increase in pause-to-speech ratio that was associated with an increase in mean pause duration from the habitual to clear speech style. Speakers in the CN group exhibited a significantly greater clear speech response than those in the PD group evidenced by a significantly larger reduction in articulation rate and a greater increase in pause-to-speech ratio between the habitual and clear speech styles. Vowel space metrics based on the distribution of formant data,

Table 3. Fixed-effect parameter estimates for the articulatory–acoustic vowel space (AAVS), vowel space hull area (VSA_{hull}), and vowel space density metrics that represent the area of outermost (VSD_{10}) and innermost (VSD_{90}) contours of the formant density distribution.

Model	Estimate	SE	df	t	p
AAVS					
Intercept	46352.6	2703.4	33.85	17.15	< .0001***
Sex	11776.9	3925.4	30.00	3.00	.0054**
Style (clear)	12147.8	1330.8	30.00	9.13	< .0001***
Group (PD)	−3703.3	3959.6	33.58	−0.94	.3563
Group × Style	−6223.9	1882.1	30.00	−3.31	.0025**
VSA_{hull}					
Intercept	985323.0	56676.0	35.08	17.39	< .0001***
Sex	107666.0	81504.0	30.00	1.32	.1960
Style (clear)	165406.0	31772.0	29.99	5.21	< .0001***
Group (PD)	−78921.0	82957.0	34.72	−0.95	.3480
Group × Style	−54127.0	44932.0	29.99	−1.21	.2380
VSD_{10}					
Intercept	808880.7	38579.0	33.58	20.97	< .0001***
Sex	158152.3	56140.8	30.00	2.82	.0085**
Style (clear)	163849.0	18334.6	29.99	8.94	< .0001***
Group (PD)	−91099.4	56513.7	33.32	−1.61	.1164
Group × Style	−70824.7	25929.1	29.99	−2.73	.0105*
VSD_{90}					
Intercept	29540.1	2742.9	56.66	10.77	< .0001***
Sex	−4064.1	3239.3	30.00	−1.26	.2193
Style (clear)	702.5	3375.4	30.00	0.21	.8365
Group (PD)	−9642.9	3971.2	55.71	−2.43	.0184
Group × Style	2316.1	4773.5	30.00	0.49	.6311

Note. The intercept is mapped to the control group in the habitual style. PD = Parkinson disease.

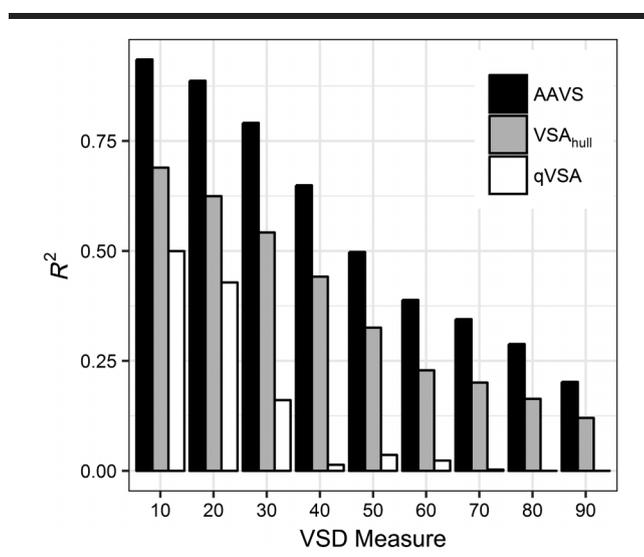
* $p < .0125$. ** $p < .01$. *** $p < .001$.

including the AAVS and VSD_{10} , reflected these between-group differences in the clear speech response. Specifically, CN speakers exhibited a greater increase in the AAVS and VSD_{10} between the habitual and clear speech styles than speakers with PD. This between-group difference in the clear speech response was not observed for the perimeter-based VSA_{hull} . Finally, the only vowel space metric for which there was a difference between the groups in the habitual speech style was VSD_{90} , which represented the area of the densest region of formant space.

Effect of PD on Vowel Space

Relative to work examining vowel space area, prior reports suggest that speakers with PD exhibit significantly smaller vowel space area than controls (e.g., Hsu et al., 2017; Tjaden et al., 2013; Whitfield & Goberman, 2014). However, other work has reported between-group differences in vowel space area that are not statistically significant (e.g., McRae et al., 2002; Ruzs et al., 2011; Sapir et al., 2007, 2010; Weismer et al., 2001). For example, Weismer et al. (2001) found no significant differences in traditional vowel space area between speakers with and without PD. Similarly, no differences between speakers with and without PD were observed in the current study for working vowel space metrics that were based on the perimeter (i.e., VSA_{hull}),

Figure 5. Coefficient of determination (R^2) quantifying the pairwise relationship between the nine vowel space density (VSD) measures and the articulatory–acoustic vowel space (AAVS), vowel space hull area (VSA_{hull}), and quadrilateral vowel space area (qVSA).



peripheral density-based envelope (i.e., VSD_{10}), or variance (i.e., AAVS) of the F1–F2 traces in formant space. Additionally, the traditional point-based qVSA did not differ between speakers with PD and controls for formant frequency pairs extracted from corner vowels that were embedded with a carrier phrase.

In the current study, significant differences in habitual working vowel space were only observed between speakers with PD and healthy controls for the most central regions of formant space, reflected in the VSD_{90} metric (see Figure 4). The more perimeter-based vowel space area metrics did not reflect differences between groups in the habitual condition. Other authors have also suggested that speakers with PD exhibit greater vowel centralization or reduction that may not be reflected in traditional vowel space metrics (e.g., Sapir et al., 2010; Whitfield & Goberman, 2014). Results of the measure of working formant space examined in the current study augment our current understanding of speech impairment in PD. The current study observed that there were no differences between speakers with PD and controls for VSA_{hull} , VSD_{10} , and the point-based qVSA, suggesting that the total peripheral formant space may only slightly differ between speakers with and without PD. However, the densest region of the formant distribution was restricted to a smaller centralized area for speakers with PD compared to controls. Therefore, it is possible that, although the formant frequency excursions for some speakers with PD may reach vowel targets in peripheral formant regions that are similar to CN speakers, the majority of articulatory–acoustic behavior is likely restricted to a smaller region of formant space. These results provide evidence reconciling why certain studies fail to detect differences between

speakers with PD and healthy controls using point-based vowel space metrics.

Effects of PD on Clear Speech

Whereas some authors have reported that speakers with PD exhibit significant increases in the traditional vowel quadrilateral area between habitual and clear speech styles (e.g., Tjaden et al., 2013), others have reported nonsignificant changes in vowel space between habitual and clear speech for speakers with PD (e.g., Goberman & Elmer, 2005). For example, Goberman and Elmer (2005) reported that there was no significant clarity-related increase in traditional qVSA calculated from formant frequency pairs extracted from the midpoint of the corner vowels spoken in a carrier phrase. In the current study, speakers with PD exhibited significant increases in the AAVS, VSD₁₀, and VSA_{hull} (see Figure 4), as well as the point-based qVSA, between the habitual and clear speech styles. Recent work by Tjaden et al. suggests that speakers with PD do exhibit significant increases in qVSA between habitually produced speech and several clear speech variants (e.g., Lam & Tjaden, 2016; Tjaden et al., 2014). This work shows that the magnitude of the clear speech response and, therefore, the magnitude of the clarity-related increase in vowel space area are affected by the instruction used to elicit clear speech (e.g., Lam & Tjaden, 2016). Given that nearly all vowel space metrics significantly increased from the habitual to clear speech style, the instruction used in the current study to elicit clear speech was effective.

Prior investigations using the AAVS have reported significant increases in the AAVS related to speech style manipulation for both speakers with PD (Whitfield & Goberman, 2014) and healthy younger adult controls (Whitfield, Dromey, et al., 2018; Whitfield & Goberman, 2017). The prior study examining clear speech in speakers with PD reported that speakers with PD exhibited a 23% increase in AAVS, which is greater than the 14% increase observed in the current study. However, the study by Whitfield and Goberman (2014) calculated the AAVS from formant trajectories extracted from one sentence, whereas the current study used formant trajectories extracted from an entire reading passage. It is possible that speakers with PD exhibited cue fade over the course of the reading task. For example, data from Skodda and Schlegel (2008) suggest that speakers with PD may exhibit a greater acceleration of speaking rate across a speaking task than controls, potentially indicating worsening hypokinesia or loss of speech motor energization over the course of a speaking task. It is therefore possible that the initial clear speech response fades over the course of the speaking task, potentially accounting for the smaller clear speech effect observed in the PD group.

Similar to the results for the VSA_{hull} and qVSA, most authors have reported that speakers with PD exhibited a comparable clarity-related increase in traditional vowel quadrilateral area to controls (e.g., Lam & Tjaden, 2016; Tjaden et al., 2013). In recent studies, Tjaden et al. reported that there were no statistically significant Group × Style interactions,

suggesting that there was a comparable increase in quadrilateral formant space between the habitual and clear speech styles for both speakers with PD and healthy controls (e.g., Lam & Tjaden, 2016; Tjaden et al., 2013). The current results for the VSA_{hull} and qVSA are in line with these prior accounts. However, results of the VSD₁₀ and AAVS models suggested that speakers with PD exhibited a significantly smaller increase in formant space from the habitual to clear speech styles than healthy controls did (see Figure 4). Additionally, between the habitual and clear speech styles, speakers with PD exhibited a reduction in articulation rate and an increase in pause duration that were significantly smaller than that observed for the CN speakers (see Figure 2). Together, these data suggest that the magnitude of the clear speech response was significantly less for speakers with PD exhibited than controls. Therefore, the current results may suggest vowel space metrics based on the distribution of formant data (i.e., variability and density) may be more sensitive to subtle differences in vowel articulation than metrics based on the perimeter of formant space.

Work by other authors suggests that within-speaker changes in formant space are often moderately to strongly related to changes in articulatory kinematic space for speakers with and without dysarthria (e.g., Lee, Littlejohn, & Simmons, 2017; Lee, Shaiman, & Weismer, 2016; Mefferd, 2015; Mefferd & Green, 2010; Whitfield, Dromey, et al., 2018). A recent study observed moderate-to-strong associations within speakers between working vowel space metrics (i.e., the AAVS and VSA_{hull}) and their kinematic equivalents that were calculated from lingual markers (Whitfield, Dromey, et al., 2018). Other work suggests that changes in articulation rate associated with clear, loud, or slow speech may, in part, account for the expansion in vowel space observed for these speaking styles (e.g., MacRae et al., 2002; Turner et al., 1995). The current results suggest that both speakers with PD and controls exhibited an increase in acoustic vowel space from habitual to clear speech. Interestingly, whereas CN speakers exhibited a significant reduction in articulation rate from the habitual to clear speech style, speakers with PD did not exhibit a significant reduction in articulation rate between styles. These data likely suggest that speakers with PD upscale articulatory gestures when using clear speech, as the increased vowel space associated with the clearer speaking style was not accompanied by a reduction in articulation rate. Additionally, the larger clarity-related expansion of the AAVS and VSD₁₀ observed for controls compared to the PD group may have resulted from both an upscaling of articulatory movement and the slowing of articulation rate that accompanied the clearer speech style.

No clarity-related changes in VSD₉₀ were observed for either group (see Figure 4). Based on these findings, it appears that clear speech was associated with an expansion of the outer bounds of formant space, whereas the densest regions of formant space remain relatively unchanged. Unlike the VSD₁₀, speakers with PD exhibited, on average, a greater clarity-related increase in VSD₉₀ than

controls, although this difference was not statistically significant. Additionally, the preliminary examination of the relationship between the VSD metrics and the AAVS and VSA_{hull} suggests that more central regions of formant space provide different information than more peripheral regions (see Figure 5). It appears that within-speaker changes and between-group differences in vowel articulation related to speech style manipulation may not be uniform across formant space.

In summary, the current results support the use of working vowel space metrics as each metric tracked within-speaker changes in speech style manipulation and several detected between-group differences in articulatory–acoustic behavior. The AAVS, VSA_{hull} , and VSD_{10} , as well as the traditional point-based qVSA, tracked clarity-related changes in articulation. Clarity-related increases in the VSD_{90} were not observed. Additionally, the VSD_{10} and AAVS were sensitive to differences in the magnitude of the clear speech response between speakers with PD and controls. The current findings, along with prior studies (e.g., Story & Bunton, 2017; Whitfield, Dromey, et al., 2018; Whitfield & Goberman, 2014, 2017), suggest that working vowel space metrics calculated from the distribution (e.g., variability and density) of time-varying formant trajectories are highly sensitive to within-speaker changes in speech articulation associated with speech style manipulation. Therefore, these metrics may provide a more sensitive and, therefore, more accurate means of tracking within-speaker changes in articulation related to disease progression or intervention.

Relations Among Vowel Space Metrics

The strongest relationship between qVSA and the measures of working formant space was the association between qVSA and AAVS, with the qVSA accounting for 55% of the variance in the AAVS. Interestingly, the relationship between the qVSA and VSA_{hull} was weaker, with the qVSA accounting for only 35% of the variation in VSA_{hull} . The moderate-to-weak relationships observed between the point-based and working vowel space metrics likely result from the different contexts from which they were measured. For example, Kuo and Weismer (2016) found a more centralized formant pattern for connected speech tasks (i.e., reading and conversation) than for vowel formants extracted from a carrier phrase, suggesting that the nature of the speaking task affects vowel distinctiveness and, thus, the F1–F2 pattern.

The current study revealed that the AAVS, VSA_{hull} , and VSD metrics provide related, though subtly different, characterization of formant space of the reading passage. This was expected as each metric derived a vowel space area measurement using different aspects of the formant data (i.e., variability, perimeter, density distribution). Among the measures that were most strongly related were the AAVS and VSD_{10} and the AAVS and VSA_{hull} . Despite the strong relationship between the AAVS and VSA_{hull} ($r^2 = .81$), however, these metrics yielded a different pattern of

results that would have affected interpretation of the current results if only one had been measured. Specifically, although both metrics tracked increases in formant space associated with clear speech, the AAVS detected between-group differences in the clear speech response that were not observed for the VSA_{hull} metric. The current results also revealed that the strength of the relationship between VSD and the AAVS and VSA_{hull} decreases as the VSD measure is calculated from the area of the densest regions of formant space. For example, VSD_{10} was very strongly correlated with the AAVS ($r^2 = .94$), whereas VSD_{90} was moderate to weak ($r^2 = .20$). Additionally, the densest regions of formant space reflect entirely different information on vowel articulation than more perimeter-based vowel space metrics as VSD_{90} yielded a different pattern of results than the three other metrics. The lack of redundancy in the pattern of results suggests that the AAVS, VSA_{hull} , and VSD metrics uniquely characterize various aspects of formant space. Future work should continue to systematically examine these measures to determine which metrics best characterize intraspeaker and interspeaker variations in speech articulation related to disorder, style, and treatment.

Although further investigation is warranted to determine which metrics best characterize various aspects of formant space, there are several considerations that may inform measure selection. For example, the current article introduced and examined several examples of VSD metrics that may prove useful in characterizing formant space. Prior authors have also suggested that VSD metrics are sensitive to differences between speaker groups (R. A. Fox & Jacewicz, 2017; Story & Bunton, 2017). However, several parameters must be investigated or at least reported to allow for across-study comparisons. For example, the length of the speech sample must be considered when examining VSD. The current sample utilized paragraph-length samples that allowed a reasonable distribution of formant data across the F1–F2 space. For shorter sentence-length utterances, the densest regions of formant space would likely be located near the F1–F2 region associated with longer vocalic portions of the stressed syllables because they are of a relatively longer duration. Additionally, several computational parameters used to create the formant density distribution influence the various VSD metrics. First, the number of bins into which the F1–F2 grid is parsed may affect the density distribution, with a finer mesh being more sensitive to local concentrations of data in formant space but potentially providing less dynamic resolution. Second, the smoothing algorithm and parameters that are used may affect the density distribution. These parameters should be constructed in a manner that allows the investigator to answer a specific research question. In the current investigation, VSD metrics were used to examine global changes in continuous formant traces from a reading passage, whereas prior work using VSD metrics have examined repeated word productions to examine subtle differences in vowel space associated with dialect (e.g., R. A. Fox & Jacewicz, 2017). Future work should parametrize and optimize these variables for a number of different speech

stimuli and research purposes. Although further parametrization of these metrics is warranted, VSD metrics likely offer a robust means of characterizing the entire distribution of formant space.

Based on the findings of the current study and our prior work, the AAVS is another potential metric that may be well suited for tracking within-participant changes in speech behavior. For speech samples of sufficient length, such as reading passages, the AAVS provides an accurate and sensitive measure of working vowel space. A preliminary investigation suggests that, within the first half of a reading passage, the AAVS converges to a stable value that is within 5% of the AAVS of the entire passage (Whitfield, Gravelin, et al., 2018). Given the sensitivity of the AAVS to speech style manipulation, the AAVS may be a viable option for quantifying within-speaker changes in vowel space associated with different speech tasks or styles, as well as longitudinal changes in vowel articulation related to disease progression or treatment.

The current data suggest that, although traditional point-based vowel space metrics extracted from a carrier phrase may be used to detect clarity-related changes, these metrics are not strongly associated with the vowel space characteristics of connected speech. Additionally, data from previous research suggest that traditional point-based vowel space area metrics often exhibit a large between-participant variation and fail to detect differences in vowel articulation between speaking styles and speaker groups (e.g., Goberman & Elmer, 2005; McRae et al., 2002; Rusz et al., 2011; Sapir et al., 2007, 2010; Whitfield, Dromey, et al., 2018; Whitfield & Goberman, 2017). Therefore, caution should be taken when interpreting group-level trends for traditional, point-based vowel space metrics. Finally, alternative approaches to quantifying qVSA may improve the representativeness of the measure. For example, computing qVSA from the mean or centroid of several corner vowel tokens that occur within a connected speech context may improve the performance of these point-based metrics (e.g., Lam & Tjaden, 2016; Tjaden et al., 2013; Sandoval et al., 2013). Additionally, quantifying qVSA from the density distribution or cluster analysis of the vowel nuclei may also improve the representativeness of vowel space area measurements (e.g., Sandoval et al., 2013; Story & Bunton, 2017).

Limitations and Future Directions

In addition to the considerations for VSD discussed above, a few key limitations of the current study should be addressed. First, the current study examined vowel space metrics for a connected speech sample using semiautomatic formant extraction. Therefore, error in the formant frequency estimation was possible, as even semiautomated approaches can result in erroneous output. However, this approach has been shown to outperform other formant extraction algorithms used in open-source software packages, specifically PRAAT and WaveSurfer (Mehta et al., 2012). Second, these measures were calculated from the

formant trajectories of the entire passage and therefore represent a composite estimate of working vowel space for that passage. This approach may have missed subtle changes in vowel articulation that may have occurred over the duration of the speaking task. Future work should consider a window estimation process for examining local changes in vowel space across the speaking task. Third, formant traces examined in the current investigation were extracted continuously and were, therefore, not directly linked to the specific phonetic intervals that occurred over the course of the reading passage. Thus, the extent to which clear speech production yielded peripheralization of vowel “targets” could not be determined. Rather, the current study observed an expansion of global formant space with clear speech production. Future work should clarify the extent to which this expansion is linked to expansion of these global metrics of formant space and is associated with greater distinctiveness and peripheralization of vowel target productions. In addition, the current data did not examine perceptual measures of clear speech to quantify perceptual differences between the groups in speech clarity. Although a prior investigation by Whitfield and Goberman (2017) observed a moderate-to-strong relationship between the clarity-related change in the AAVS and listener ratings of clarity, that investigation included healthy CN talkers. Therefore, future investigations could continue to examine the relationship between these acoustic vowel space measures and perceptual measures of speech clarity and intelligibility. Finally, the current study only examined one reading passage. Therefore, these findings must be considered preliminary until they are replicated with other speech materials.

Conclusions and Implications

Findings from the current investigation have several implications for future research and clinical practice. First, these data may suggest that speakers with PD exhibit less of a clear speech response than neurologically healthy controls over the course of a reading passage. This finding was observed for speech rate, pause, and vowel space metrics, confirming that clarity-related modulation of articulation and prosody was less robust for speakers with PD than controls. However, visual comparison of the average articulation rate, pause duration, and vowel space metrics for the habitual style of the CN group and the clear style of the PD group suggests that speakers with PD exhibited improvements in speech articulation and prosody that were within the average range of the CN group. Additionally, the four working vowel space metrics examined in the current study did not yield the same pattern of statistical results, suggesting that these metrics are not redundant and uniquely quantify different aspects of formant space. Furthermore, the current findings also suggest that changes in formant space associated with modulation of speech clarity are not uniform across formant space, supporting the use of several vowel space metrics to quantify speech behavior.

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