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Research Article

Vowel Acoustics in Dysarthria: Speech Disorder Diagnosis and Classification

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Purpose: The purpose of this study was to determine the extent to which vowel metrics are capable of distinguishing healthy from dysarthric speech and among different forms of dysarthria.
Method: A variety of vowel metrics were derived from spectral and temporal measurements of vowel tokens embedded in phrases produced by 45 speakers with dysarthria and 12 speakers with no history of neurological disease. Via means testing and discriminant function analysis (DFA), the acoustic metrics were used to (a) detect the presence of dysarthria and (b) classify the dysarthria subtype.
Results: Significant differences between dysarthric and healthy control speakers were revealed for all vowel metrics. However, the results of the DFA demonstrated some metrics (particularly metrics that capture vowel distinctiveness) to be more sensitive and specific predictors of dysarthria. Only the vowel metrics that captured slope of the second formant (F2) demonstrated between-group differences across the dysarthrias. However, when subjected to DFA, these metrics proved unreliable classifiers of dysarthria subtype.
Conclusion: The results of these analyses suggest that some vowel metrics may be useful clinically for the detection of dysarthria but may not be reliable indicators of dysarthria subtype using the current dysarthria classification scheme.

Key Words: acoustics, dysarthria, speech production, diagnostics

The work discussed herein is the first of two articles investigating degraded vowel acoustics in dysarthria. The larger goal of this project was to identify sensitive acoustic metrics that have the potential to predict listener performance. Such information is useful in the development of cognitive–perceptual models of intelligibility (Lansford, Liss, Caviness, & Utianski, 2011). In the present article, we explore the extent to which acoustic metrics capturing vowel production deficits in dysarthria are capable of distinguishing healthy from dysarthric speech and among the different forms of dysarthria. In our companion article (see Lansford & Liss, 2014), we examine the correspondence between dysarthric vowel acoustics and vowel identification by healthy listeners.

Distorted vowel production is a hallmark characteristic of dysarthria, irrespective of the underlying neurological condition (Darley, Aronson, & Brown, 1969a, 1969b, 1975; Duffy, 2005). In general, vowels produced by individuals with dysarthria are characterized by articulatory undershoot (i.e., failure of the produced vowel to reach canonical formant frequencies), resulting in compressed or reduced working vowel space (R. Kent & Kim, 2003). The articulatory mechanisms implicated in vowel production deficits in dysarthria include reduced excursion and velocity of lingual, lip, and jaw movements and aberrant movement timing (see Yunusova, Weismer, Westbury, & Lindstrom, 2008, for a brief review of the literature). The acoustic consequences of such vowel production deficits have been widely investigated (e.g., Y.-J. Kim, Weismer, Kent, & Duffy, 2009; Rosen, Goozee, & Murdoch, 2008; Turner, Tjaden, & Weismer, 1995; Watanabe, Arasaki, Nagata, & Shouji, 1994; Weismer, Jeng, Laures, Kent, & Kent, 2001; Weismer & Martin, 1992; Ziegler & von Cramon, 1983a, 1983b, 1986) and are summarized by K. Kent, Weismer, Kent, Vorperian, and Duffy (1999) as including centralization of formant frequencies, reduction of vowel space area (i.e., mean working vowel space), and abnormal formant frequencies for both high and front vowels. Other acoustic findings detailed are vowel formant pattern instability and reduced F2 slopes (R. D. Kent, Weismer, Kent, & Rosenbeck, 1989; Y.-J. Kim et al., 2009; Weismer et al., 2001; Weismer & Martin, 1992).

Although a variety of acoustic metrics have been derived to capture vowel production deficits in dysarthria, it remains unclear whether such metrics can be used to differentiate speakers with dysarthria from healthy controls.

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Relative to healthy control speakers, movement of the second formant during vowel production, captured in a variety of contexts (e.g., consonant–vowel transitions, diphthongs, and monophthongs), was reduced for some dysarthric speakers (Y.-J. Kim et al., 2009; Rosen et al., 2008; Weismer et al., 2001; Weismer & Martin, 1992). Weismer and his colleagues (Weismer et al., 2001; Weismer & Martin, 1992) found shallower F2 trajectories in male speakers with dysarthria secondary to amyotrophic lateral sclerosis (ALS) relative to age- and gender-matched healthy controls. Similar results have been revealed for speakers with dysarthria secondary to Parkinson's disease (PD), stroke (Y.-J. Kim et al., 2009), and multiple sclerosis (Rosen et al., 2008).

Measures capturing overall vowel space area (quadrilateral or triangular) have demonstrated less reliable discriminability. Vowel space area (VSA), calculated as the area within the irregular quadrilateral formed by the first and second formants of the corner vowels /i/, /æ/, /a/, and /u/, was found to be reduced relative to healthy controls for male speakers with ALS (Weismer et al., 2001). However, no group differences were revealed for female speakers with ALS or for dysarthric speakers with PD relative to control speakers. Conflicting findings reported by Tjaden and Wilding (2004) revealed that quadrilateral VSA was significantly reduced for PD patients relative to healthy controls. This was not demonstrated for the speakers with multiple sclerosis (MS). Also noteworthy, the vowel space areas of patients with PD and MS did not differ significantly (Tjaden & Wilding, 2004). Sapir, Spielman, Ramig, Story, and Fox (2007) did not find significant difference in triangular VSA, calculated as the area within the triangle formed by the first and second formants of the vowels /i/, /u/, and /a/, between control and PD speakers. However, between-group differences were found for F2 of the vowel /u/ and the ratio of $F2_i/F2_u$.

To investigate the suggestion that lax vowel production may be unaffected by motor speech disorders as a result of their reduced articulatory production demands (Turner et al., 1995), Tjaden and colleagues (Tjaden, Rivera, Wilding, & Turner, 2005) derived and studied the vowel space area encompassed by the lax vowels /ɪ/, /ɛ/, and /ʊ/ in a cohort of dysarthric and healthy control speakers. This hypothesis was partially supported by the data, as lax vowel space for speakers with PD could not be differentiated from that of controls. Conversely, lax vowel space was sensitive to differences between ALS and control vowel productions. The authors speculated that the differential effects found for lax vowel spaces of subjects with PD and those with ALS may be attributed to differences in underlying pathophysiology or to overall severity differences found for the two groups (ALS more severe than PD).

Because of the inconclusive findings regarding the utility of traditional vowel space measures in the discrimination of dysarthric and healthy control vowel production, alternative methods for capturing centralization of formant frequencies in dysarthria have been proposed (see Sapir, Ramig, Spielman, & Fox, 2010; Skodda, Visser, & Schlegel, 2011). For example, the formant centralization ratio (FCR) was proposed as a vowel space metric that maximizes sensitivity to vowel centralization while minimizing interspeaker variability in formant frequencies (i.e., normalizing the vowel space; Sapir et al., 2010). The ratio, expressed as $(F2_u + F2_a + F1_i + F1_a)/(F2_i + F1_a)$, is thought to capture centralization when the numerator increases and the denominator decreases. Ratios greater than one are interpreted as indicating vowel centralization. The FCR, unlike the triangular VSA metric, was demonstrated to reliably distinguish hypokinetic vowel spaces from those of healthy control speakers (Sapir et al., 2010). Similarly, the vowel articulation index (the inverse of the FCR, initially described by Roy, Nissen, Dromey, and Sapir, 2009) reliably discriminated hypokinetic from healthy control vowel spaces (Skodda et al., 2011). The authors of these two related studies concluded that metrics that minimize interspeaker variability while maximizing vowel centralization may be more sensitive to mild dysarthria than traditional VSA metrics.

Whereas vowels produced by individuals with dysarthria may be characterized by articulatory undershoot, the working space of vowels may be differentially affected by the nature of the production deficit. Specifically, vowel space distortions, resulting in spectral overlap (i.e., overlapping boundaries of neighboring vowels), may differentially affect high versus low or front versus back contrasts. Traditional and alternative metrics proposed to capture vowel centralization may be insensitive to such variable vowel space warping. This issue is not trivial as differential production characteristics of vowels very likely influence the nature of the communication disorder caused by the dysarthria. For example, a greater occurrence of tongue-height errors (e.g., "bet" for "bit") may be revealed in individuals with a tighter articulatory working space of the front vowels. Thus, metrics capturing dispersion of vowels (i.e., relative distance between vowel pairs or groups of vowels) may offer an informative alternative to traditional vowel space area metrics. To date, metrics capturing dispersion of vowels have not been used to differentiate dysarthric from healthy control vowel production. However, recently reported evidence suggests that dispersion metrics are predictive of overall intelligibility in dysarthria secondary to cerebral palsy (H. Kim, Hasegawa-Johnson, & Perlman, 2011).

Although the results of the investigations previously described were largely dependent on type of dysarthria (among other factors, such as sex of the speaker and severity of the disorder), to date, very little attention has been paid to quantifying the vowel production deficits associated with the specific dysarthrias. Recent attempts to quantify the dysarthrias by using acoustic metrics have been met with mixed results. For example, metrics capturing temporal and spectral aspects of rhythm were used to reliably categorize speakers according to their dysarthria diagnoses (Liss, LeGendrew, & Lotto, 2010; Liss et al., 2009). Conversely, however, a variety of acoustic metrics, including VSA and F2 slope, better classified a large heterogeneous cohort of speakers with dysarthria by the severity of their speech disorder than by dysarthria diagnosis (Y.-J. Kim, Kent, & Weismer, 2011). Such findings, particularly when coupled with unreliable classification by trained listeners blinded to underlying medical etiology (e.g., Fonville et al., 2008; Van der Graff et al., 2009; Zyski & Weisiger, 1987), have led some to challenge the current gold standard in dysarthria diagnostic practices. In lieu of the current diagnostic practices, known as the Mayo Clinic approach (Darley, Aronson, & Brown, 1969a, 1969b, 1975), Weismer and Kim (2010) suggested a taxonomical approach to dysarthria diagnosis. The overarching goal of this approach is to identify a core set of deficits (i.e., perceptual similarities) common to most, if not all, speakers with dysarthria. Identification of acoustic similarities would permit the detection of differences that reliably distinguish different types of motor speech disorders irrespective of etiology. Weismer and Kim offered a number of potential acoustic "similarities," including F2 slope and compressed vowel space. The implications of this approach, however, extend beyond that of classification, as identification of acoustic similarities would permit principled investigation of their impact on speech intelligibility.

In the present investigation, we aimed to evaluate the utility of a variety of vowel space metrics in the differentiation of vowel productions made by individuals with and without dysarthria. In addition, the extent to which these metrics could be used to differentiate among the four dysarthria subtypes (ataxic, hypokinetic, hyperkinetic, and mixed flaccid-spastic) was assessed. Establishing the sensitivity of measures or groups of measures to classify speech status is a useful step in the development of an objective tool for classifying vowel production deficits. In our associated companion article (see Lansford & Liss, 2014), we leverage the results of this study to examine whether the acoustic metrics can predict intelligibility and vowel identification. Although these investigations are limited to vowel production deficits in dysarthria, primarily of the vocal tract filter, in no way should the potential contributions of imprecise consonant production or aberrant sound source function to the detection and classification of dysarthria be minimized. Rather, it is the goal of these works to contribute a small piece to the development of a cognitive–perceptual framework, which should include segmental (e.g., vowels and consonants) and suprasegmental acoustic features, for conceptualizing the intelligibility deficits associated with dysarthric speech (Lansford et al., 2011).

Method

Study Overview

The goal of this experiment was to identify vowel metrics that differentiate (a) disordered from nondisordered speakers and (b) the dysarthria subtypes. Toward this end, means testing (e.g., *t* tests and analyses of variance) and stepwise discriminant function analysis (DFA) were conducted.

Speakers

Speech samples from 57 speakers (29 male), collected as part of a larger study (Liss, Utianski, & Lansford, 2013), were used in the present analysis. Of the 57 speakers, 45 were diagnosed with one of four types of dysarthria: ataxic dysarthria secondary to various neurodegenerative diseases (ataxic; $n = 12$), hypokinetic dysarthria secondary to idiopathic Parkinson's disease (PD; $n = 12$), hyperkinetic dysarthria secondary to Huntington's disease (HD; $n = 10$), or mixed flaccid-spastic dysarthria secondary to amyotrophic lateral sclerosis (ALS; $n = 11$). Speech samples collected from a majority of these dysarthric speakers have been analyzed for other projects conducted in the Motor Speech Disorder (MSD) lab at Arizona State University (e.g., Liss et al., 2009, 2010). The remaining 12 speakers had no history of neurological impairment and served as the healthy control group. All speakers spoke American English natively and without any significant regional dialects and were recruited from the Phoenix, Arizona, metropolitan area. The disordered speakers were selected from the pool of speech samples on the basis of the presence of the cardinal features associated with their corresponding dysarthria. Speaker age, gender, and severity of impairment are provided in Table 1. Two trained speech-language pathologists affiliated with the MSD lab at Arizona State University (including the second author) independently rated severity of each speaker's impairment from a production of "The Grandfather Passage." Perceptual ratings of *mild, moderate,* and *severe* were corroborated by the intelligibility data (percentage of words correct on a transcription task) described in Lansford and Liss (2014).

Stimuli

All speech stimuli, recorded as part of the larger investigation, were obtained during one session (on a speaker-by-speaker basis). Participants were fitted with a head-mounted microphone (Plantronics DSP-100), seated in a sound-attenuating booth, and instructed to read stimuli from visual prompts presented on the computer screen. Recordings were made using a custom script in TF32 (Milenkovic, 2004; 16-bit, 44 kHz) and were saved directly to disc for subsequent editing using commercially available software (SoundForge; Sony Corporation, Palo Alto, CA) to remove any noise or extraneous articulations before or after target utterances. The speakers read 80 short phrases aloud in a "normal, conversational voice." The phrases all contained six syllables and were composed of three to five mono- or disyllabic words, with low semantic transitional probability. The phrases alternated between strong and weak syllables, where strong syllables were defined as those carrying lexical stress in citation form. The acoustic features and listeners' perceptions of vowels produced within the *strong* syllables were the targets of analysis.

Of the 80 phrases, 36 were selected for the present analysis on the basis of the occurrence of the vowels of interest (see Appendix A). A counterbalanced design for the phrases and speakers was developed to optimize the collection of perceptual data, which is reported in our companion article (Lansford & Liss, 2014). Briefly, we divided the 36 phrases into two 18-phrase stimulus sets, balanced such that each of the 10 vowels (/i/, /ɪ/, /e/, /ɛ/, /æ/, /u/, /ʊ/, /o/, /a/, and /^/) was represented equally. In addition, the speaker composition of each stimulus set was balanced for severity of the speech impairment (on the basis of clinical judgment; see Table 1), dysarthria diagnosis, and sex of the speaker. Within each stimulus set, a vowel was produced a minimum of four times;

Table 1. Dysarthric speaker demographic information per stimulus set.

Speaker	Sex	Age	Medical etiology	Severity of speech disorder
			Set 1	
ALSF2	F	75	ALS	Severe
ALSF8	F	63	ALS	Moderate
ALSM1	M	56	ALS	Moderate
ALSM5	M	50	ALS	Mild
ALSM7	M	60	ALS	Severe
AF2	F	57	Multiple sclerosis/ataxia	Severe
AF6	F	57	Friedrich's ataxia	Moderate
AF7	F	48	Cerebellar ataxia	Moderate
AM1	M	73	Cerebellar ataxia	Severe
AM5	M	84	Cerebellar ataxia	Moderate
AM6	M	46	Cerebellar ataxia	Moderate
HDF5	F	41	Huntington's disease	Moderate
HDF6	F	57	Huntington's disease	Severe
HDM3	M	80	Huntington's disease	Moderate
HDM10	M	50	Huntington's disease	Severe
HDM12	M	76	Huntington's disease	Moderate
PDF1	F	64	Parkinson's disease	Mild
PDF7	F	58	Parkinson's disease	Moderate
PDF9	F	71	Parkinson's disease	Mild
PDM8	M	77	Parkinson's disease	Moderate
PDM9	M	76	Parkinson's disease	Moderate
PDM15	M	57	Parkinson's disease	Moderate
			Set 2	
ALSF5	F	73	ALS	Severe
ALSF7	F	54	ALS	Moderate
ALSF9	F	86	ALS	Severe
ALSM3	M	41	ALS	Mild
ALSM4	M	64	ALS	Moderate
ALSM8	M	46	ALS	Moderate
AF1	F	72	Cerebellar ataxia	Moderate
AF8	F	65	Cerebellar ataxia	Moderate
AF9	F	87	Cerebellar ataxia	Severe
AM3	M	79	Cerebellar ataxia	Moderate–severe
AM4	M	46	Cerebellar ataxia	Moderate
AM8	M	63	Cerebellar ataxia	Moderate
HDF1	F	62	Huntington's disease	Moderate
HDF3	F	37	Huntington's disease	Moderate
HDF7	F	31	Huntington's disease	Severe
HDM8	M	43	Huntington's disease	Severe
HDM11	M	56	Huntington's disease	Moderate
PDF3	F	82	Parkinson's disease	Mild
PDF5	F	54	Parkinson's disease	Moderate
PDF6	F	65	Parkinson's disease	Mild
PDM1	M	69	Parkinson's disease	Severe
PDM10	M	80	Parkinson's disease	Moderate
PDM12	M	66	Parkinson's disease	Severe

Note. F = female; M = male; ALS = amyotrophic lateral sclerosis.

thus, the acoustic analyses were limited to four tokens per vowel per speaker.[1]

Spectral and Temporal Measurements

All speech samples were analyzed using Praat (Boersma & Weenik, 2006). Vowels were identified and segmented by two trained members of the MSD lab at Arizona State University via visual inspection of the waveform and spectrogram according to standard segmentation criteria (Peterson & Lehiste, 1960; see Liss et al., 2009, for a detailed description of the vowel segmentation criteria used). The first and second formants were measured in hertz at each vowel's onset (20% of vowel duration), midpoint (50% of vowel duration), and offset (80% of vowel duration). The midpoint formant values were interpreted to represent the vowel's steady state. The onset and offset measurements along with vowel duration were obtained to derive vowel metrics that captured formant movement over time (e.g., F2 slope metrics). To determine inter- and intrarater reliability of the formant measurements, 10% of all vowel tokens were remeasured by same and different judges. Inter- and intrarater reliability (Cronbach's alpha) were .889 and .886 for F1 and .884 and .819 for F2 measurements, respectively. The signed average differences between F1 initial measurements and those made by inter- and intraraters were 15.63 Hz and 8.81 Hz, respectively. The signed average difference between F2 initial measurements and those made by inter- and intraraters were 14.19 Hz and 42.38 Hz, respectively. In most cases, the formant measurements made by the initial judge were used in the analysis. However, in the instances it was clear that a significant discrepancy between the Time 1 and Time 2 measurements was due to miscoding, the formant frequencies were remeasured by the first author and used in the analysis.

Derived Vowel Metrics

The spectral and temporal measurements were used to derive a variety of metrics designed to capture mean working vowel space. These metrics include traditional vowel space area metrics, an alternative metric of vowel centralization, metrics capturing vowel space dispersion, and F2 slope metrics. Each subclass of derived vowel metrics is discussed briefly below. In addition, all metrics and their computation are summarized in Table 2.

Traditional vowel space metrics. As discussed in the introduction of this article, a variety of computations have been used to estimate vowel space area in dysarthria. Thus, to assess the ability of each estimate to detect the presence of dysarthria, vowel space area in this investigation was expressed in three ways: (a) VSA of the irregular quadrilateral formed by the first and second formants of the corner vowels /i/, /æ/, /a/, and /u/; (b) VSA of the triangle formed by the first and second formants of the vowels /i/, /a/, and /u/; and (c) VSA of the triangle formed by the first and second formants of the lax vowels /ɪ/, /ɛ/, and /ʊ/.

Alternate vowel space area metrics. Recent evidence supports the use of the formant centralization ratio (FCR) to explore vowel production deficits associated with hypokinetic dysarthria (Sapir et al., 2010; Skodda et al., 2011). The FCR was included in this investigation to assess its ability to detect dysarthria in a cohort of speakers with greater diversity of dysarthria type and presence of perceptual features.

Dispersion and distance vowel space metrics. Several established and novel dispersion and distance metrics were

[1]The vowel /ʊ/ is represented in only three of the 80 experimental phrases. Because many of the vowel space area acoustic metrics require measurements from all 10 vowels, measurements of /ʊ/ were derived from all three phrases per speaker, irrespective of their assigned stimulus set.

Table 2. Derived vowel metrics.

Vowel metric	Description
Quadrilateral VSA	Heron's formula was used to calculate the area of the irregular quadrilateral formed by the corner vowels (i, æ, a, u) in F1 × F2 space. Toward this end, the area (as calculated by Heron's formula) of the two triangles formed by the sets of vowels /i/, /æ/, /u/ and /u/, /æ/, /a/ are summed. Heron's formula is as follows: $\sqrt{s(s-a)(s-b)(s-c)}$, where s is the semiperimeter of each triangle, expressed as $s = ½ (a + b + c)$, and a, b, and c each represent the Euclidean distance in F1 × F2 space between each vowel pair (e.g., /i/ to /æ/).
Triangular VSA	Triangular vowel space area was constructed with the corner vowels (i, a, u). It was derived using the equation outlined by Sapir and colleagues (2010) and is expressed as $ABS\{[F1_i \times (F2_a - F2_u) + F1_a \times (F2_u - F2_i) + F1_u \times (F2_i - F2_a)]/2\}$. ABS in this equation refers to absolute value.
Lax VSA	Lax vowel space area was constructed with the lax vowels /ɪ, ɛ, ʊ/. The equation used to derive triangular vowel space area was used to derive lax vowel space area.
FCR	This ratio, expressed as $(F2_u + F2_a + F1_i + F1_a)/(F2_i + F1_a)$, is thought to capture centralization when the numerator increases and the denominator decreases. Ratios greater than 1 are interpreted to indicate vowel centralization.
Mean dispersion	This metric captures the overall dispersion (or distance) of each pair of the 10 vowels, as indexed by the Euclidean distance between each pair in the F1 × F2 space.
Front dispersion	This metric captures the overall dispersion of each pair of the front vowels (i, ɪ, e, ɛ, æ). Indexed by the average Euclidean distance between each pair of front vowels in F1 × F2 space.
Back dispersion	This metric captures the overall dispersion of each pair of the back vowels (u, ʊ, o, a). Indexed by the average Euclidean distance between each pair of back vowels in F1 × F2 space.
Corner dispersion	This metric is expressed by the average Euclidean distance of each of the corner vowels (i, æ, a, u) to the center vowel /^/.
Global dispersion	Mean dispersion of all vowels to the global formant means (Euclidian distance in F1 × F2 space).
Average F2 slope	The absolute values of the F2 slopes from vowel onset to offset were averaged across the entire vowel set.
Dynamic F2 slope	The absolute values of F2 slopes associated with the most dynamic vowels (æ, ^, ʊ) were averaged. Dynamic vowels were so designated based on the work of Neel (2008).

Note. VSA = vowel space area; FCR = formant centralization ratio.

calculated to capture the many ways in which the vowel space may be warped. For example, depending on the nature of the vowel production deficit, the vowel space associated with front and/or back vowels may be differentially compressed. To capture front and back vowel space compression, mean dispersions of the front and back vowels were derived for each speaker. In addition, dispersion metrics have the potential to capture vowel reduction and distinctiveness. Thus, the following metrics were calculated for each speaker to be included in the analysis: mean dispersion of the corner vowels to /^/, mean dispersion of all vowels to the global formant means (global dispersion), and mean dispersion of all vowel pairs (mean dispersion).

F2 slope metrics. Finally, reduced F2 slope is reportedly related to perceptual decrements associated with dysarthria (e.g., R. D. Kent et al., 1989; Y.-J. Kim et al., 2009; Weismer et al., 2001). Accordingly, the absolute values of the F2 slopes from vowel onset to offset were averaged across the entire vowel set. Additionally, the absolute values of F2 slopes associated with the most dynamic vowels were averaged and included in this analysis. It is important to note that the F2 slope measurements derived in this article differ from others (cf. R. D. Kent et al., 1989; Y.-J. Kim et al., 2009) in that they are simply measures of rise, sampled from two points in time, over run (i.e., formant change from onset to offset divided by the vowel's duration). Thus, the results of this investigation should be related to previous work with caution as the current metrics are meant to reflect a snapshot of formant movement over time.

Data Analysis

The derived vowel metrics per speaker were subjected to a series of analyses designed to identify metrics that reliably distinguish dysarthric from healthy control vowel production. Toward this end, independent samples t tests were conducted to assess the differences between the vowel metrics derived from dysarthric and healthy control speakers. Because of the number of moderately correlated variables under investigation (11 variables; see Appendix B), a conservative p value of .0045 (.05/11) was applied to control the experiment-wise error rate. The metrics that demonstrated significant between-group differences were subsequently subjected to DFA to assess their abilities to differentiate dysarthric from healthy control speakers.

To assess the vowel metrics' sensitivity to dysarthria subtype, a series of one-way analyses of variance (ANOVAs) was conducted. Again, a conservative p value of .0045 was applied to control the experiment-wise error rate. Any metrics that demonstrated between-group differences were subjected to DFA to classify the dysarthric speakers according to their dysarthria subtype.

Results

Analysis 1: Dysarthria Versus Healthy Control

Despite the unequal sample sizes, Levene's test for equality of variances revealed equal variances for all but two vowel metrics (average F2 slope and the FCR). Nonparametric

Table 3. Healthy control and dysarthric group means and results of independent samples *t* tests.

Vowel metric and group	*n*	*M*	*SD*	*t*(55)	*p*	Cohen's *d*
Quadrilateral VSA				5.056	.000*	1.62
HC	12	286,213.07	71,217.41			
D	45	174,822.17	66,928.04			
Triangular VSA				2.745	.008	0.96
HC	12	175,285.55	49,012.16			
D	45	120,378.89	64,311.64			
Lax VSA				2.202	.032	0.33
HC	12	312,88.86	19,208.13			
D	45	18,659.61	17,240.48			
FCR				–5.098	.000*	1.31
HC	12	1.07	0.05			
D	45	1.19	0.12			
Mean dispersion				3.283	.002*	1.04
HC	12	400.54	69.31			
D	45	330.46	64.76			
Front dispersion				5.503	.000*	1.82
HC	12	503.32	83.38			
D	45	345.65	89.34			
Back dispersion				3.916	.000*	1.25
HC	12	368.45	75.32			
D	45	276.13	71.86			
Corner dispersion				4.051	.000*	1.22
HC	12	563.45	120.48			
D	45	432.14	93.89			
Global dispersion				3.756	.000*	1.18
HC	12	597.56	101.37			
D	45	484.11	90.76			
Average F2 slope (Hz/ms)				4.271	.000*	1.11
HC	12	2.08	0.29			
D	45	1.55	0.61			
Dynamic F2 slope (Hz/ms)				2.927	.005	1.04
HC	12	3.21	0.70			
D	45	2.32	0.99			

Note. HC = healthy control; D = dysarthric.
*$p < .0045$.

handling of these metrics was not indicated, as the between-group differences were robust to parametric testing. Significant between-group differences were revealed for eight of the 11 vowel metrics (see Table 3 for group means, results of *t* tests, and effect sizes). With a conservative *p* value of .0045, the group differences revealed for lax VSA, triangular VSA, and dynamic F2 slope failed to reach significance. All significant between-group differences were in the expected direction (e.g., VSA smaller for dysarthric speakers).[2]

[2]It is important to note that the healthy control speakers were not age matched ($M = 25.5$, range = 21–37) to the dysarthric speakers ($M = 62.1$, range = 31–87). This matter is not insignificant given the findings of age-related vowel centralization in neurologically intact geriatric speakers (Benjamin, 1982; Liss, Weismer, & Rosenbeck, 1990; Ratstatter & Jacques, 1990; Torre & Barlow, 2009). To ensure the results were not a consequence of the age difference between the two groups of speakers, a post hoc analysis comparing the vowel space areas of the healthy controls and a younger subset of dysarthric speakers (age < 50, range 31–48, $n = 8$) revealed that the vowel space area of the healthy control speakers ($M = 286{,}213.07$ Hz^2, $SD = 71{,}217.4$) was significantly larger than that of the younger dysarthric subset ($M = 148{,}704.02$ Hz^2, $SD = 66{,}893.7$), $t(18) = -4.331$, $p < .0001$. These findings support the interpretation that the vowel space reduction revealed in this heterogeneous cohort of dysarthric speakers was a consequence of neurological impairment and not of advanced age.

The vowel metrics that demonstrated significant between-group differences were subjected to DFA to assess the ability of each to reliably discriminate dysarthric from healthy control speakers. Because of its frequent use in studies of dysarthric vowel production, triangular vowel space was included in this analysis despite failing to reach significance ($p = .008$) when the conservative *p* value was applied. The detailed results of each DFA are reported in order of classification accuracy in Table 4. Overall, the metrics classified healthy control and dysarthric speakers with accuracy scores ranging from 66.7% to 84.2%. The metric capturing mean dispersion of the front vowels best differentiated dysarthric from healthy control speakers, with a classification accuracy of 84.2%. Triangular VSA classified speakers least reliably, with approximately 67% accuracy; yet VSA calculated from the irregular quadrilateral formed by the corner vowels classified dysarthric and control speakers with 80% accuracy (the second best classifier).

Although the quantitative differences between the classifiers may seem small in some cases (e.g., <4% difference between the top two classifiers, mean front vowel dispersion and quadrilateral VSA), a closer examination of the classification data by severity of the dysarthria revealed that these

Table 4. Healthy control and dysarthric speaker classification accuracy by vowel metric.

Vowel metric and group	Predicted group HC	D	Overall accuracy (%)	Mild accuracy (%)	Moderate accuracy (%)	Severe accuracy (%)
Front dispersion			84.2	100.0	73.1	92.3
HC	11	1				
D	8	37				
Quadrilateral VSA			80.7	83.3	80.8	92.3
HC	8	4				
D	7	38				
Back dispersion			73.7	66.7	73.1	92.3
HC	7	5				
D	10	35				
Corner dispersion			73.7	33.3	73.1	92.3
HC	9	3				
D	12	33				
Global dispersion			71.9	66.7	69.2	84.6
HC	8	4				
D	12	33				
Average F2 slope			71.9	33.3	73.1	100.0
HC	9	3				
D	13	32				
FCR			70.2	50.0	65.4	76.9
HC	11	1				
D	15	30				
Mean dispersion			70.2	50.0	69.2	84.6
HC	8	4				
D	13	32				
Triangular VSA			66.7	50.0	61.5	84.6
HC	8	4				
D	15	30				

differences are not insignificant (see Table 4). For example, mean dispersion of the front vowels demonstrated a near 17% point advantage over quadrilateral VSA in accurate dysarthria classification of mildly impaired speakers. This finding is important, as detection of dysarthria, particularly in its mildest presentation, by objective acoustic metrics is a primary goal of this line of work. This will be discussed in greater detail in the Discussion.

Analysis 2: Dysarthria Subtypes

The vowel metrics calculated for the 45 speakers with dysarthria were subjected to one-way ANOVAs to identify those sensitive to possible dysarthria-specific effects. Significant between-group differences were revealed for two vowel metrics, average F2 slope and F2 slope of the most dynamic vowels (see Table 5 for ANOVA results and Table 6 for group means of metrics with significant between-group differences). To further explore the between-group differences observed in the F2 slope metrics, multiple comparison analysis were conducted. Briefly, both average F2 slope and F2 slope of the most dynamic vowels were greater for speakers diagnosed with hypokinetic dysarthria than those with ataxic or mixed flaccid-spastic dysarthrias. In addition, average F2 slope and F2 slope of the most dynamic vowels were greater for hyperkinetic speakers than for mixed flaccid-spastic speakers.

To assess the ability of the significant F2 slope metrics to distinguish among the dysarthria subtypes, we subjected each to DFA. Average F2 slope accurately classified 44.4% of the dysarthric speakers. F2 slope of the most dynamic vowels faired somewhat better, classifying 53.3% of the dysarthric speakers accurately. Examination of the DFA error patterns (see Table 7) revealed that speakers with hyperkinetic and hypokinetic dysarthria were commonly misclassified as one another by both F2 slope metrics. There were no reliable error patterns for speakers with ataxic or mixed flaccid-spastic dysarthria, other than that neither group of speakers was misclassified as hypokinetic. These error patterns mirror the results of the ANOVA and multiple comparisons described above.

Discussion

Compressed or reduced vowel space area has been demonstrated in dysarthria arising from various neurological

Table 5. Analysis of variance testing equality of means of vowel metrics for the dysarthria subtypes.

Vowel metric	$F(3, 41)$	p	η^2
Quadrilateral VSA	0.358	.783	
Triangular VSA	1.403	.256	
Lax VSA	0.208	.890	
FCR	0.672	.574	
Mean dispersion	0.436	.728	
Front dispersion	1.634	.196	
Back dispersion	0.614	.610	
Corner dispersion	0.974	.414	
Global dispersion	0.669	.576	
Average F2 slope	14.327	.000	.512
Dynamic F2 slope	12.270	.000	.473

Table 6. Group means of significant variables revealed by analysis of variance.

Vowel metric	*n*	*M*	*SD*	95% CI LL	95% CI UL
	Average F2 slope (Hz/ms)				
Ataxic	12	1.32	0.34	1.10	1.54
ALS	11	1.01	0.45	0.71	1.31
HD	10	1.70	0.32	1.47	1.93
PD	12	2.16	0.59	1.78	2.54
	Dynamic F2 slope (Hz/ms)				
Ataxic	12	1.90	0.80	1.40	2.41
ALS	11	1.51	0.81	0.97	2.05
HD	10	2.59	0.32	2.37	2.82
PD	12	3.25	0.87	2.69	3.81

Note. CI = confidence interval; LL = lower limit; UL = upper limit; HD = Huntington's disease; PD = Parkinson's disease.

Table 7. Classification summary by dysarthria subtype.

Group	Predicted group: Ataxic	ALS	HD	PD
	Average F2 slope[a]			
Ataxic	4	5	3	
ALS	3	6	2	
HD	3		3	4
PD	2		3	7
	Dynamic F2 slope[b]			
Ataxic	4	5	2	1
ALS	1	7	3	
HD	1		7	2
PD			6	6

[a]Overall accuracy = 44.4%. [b]Overall accuracy = 53.3%.

conditions, including ALS, Parkinson's disease, and cerebral palsy (Liu, Tsao, & Kuhl, 2005; Tjaden & Wilding, 2004; Weismer et al., 2001), although not universally (e.g., see Sapir et al., 2007; Weismer et al., 2001). The results of the present analysis demonstrate that speakers with dysarthria secondary to a variety of underlying medical conditions were reliably differentiated from healthy control speakers by a number of vowel metrics derived from vowels produced in connected speech.[3] Specifically, reductions in VSA and mean vowel space dispersion were revealed for speakers with dysarthria relative to healthy control speakers. Similarly, the FCR was significantly higher in dysarthric speakers as compared with the healthy controls, suggesting the presence of vowel centralization in the disordered population. This conclusion is further supported by findings that revealed reductions in mean dispersion of front and back vowels and mean dispersion between the corner vowels and /^/ in dysarthric speakers.

The results of the DFA revealed mean dispersion of front vowels to be the most reliable indicator of dysarthria, with classification accuracy exceeding 84%. In other words, the metric capturing the articulatory working space of front vowels best differentiated dysarthric and healthy control speakers. Inspection of the classification data revealed that front vowel dispersion correctly detected dysarthria in speakers with mild, moderate, and severe dysarthria with 100%, 73%, and 93% accuracy,[4] respectively. In addition, only one healthy control speaker was misclassified as having dysarthria using the metric capturing front vowel dispersion. With the high degree of accurate identification of healthy control speakers using an acoustic metric capturing front vowel working space, a follow-up question may be whether speakers with dysarthria that are erroneously classified as healthy control, presumably because their front vowel working space is acoustically "normal," present less of a perceptual challenge to listeners.

Quadrilateral vowel space area classified speakers with 80% accuracy and outperformed all other vowel metrics, with the exception of front vowel dispersion. However, it is important to note that the composition of misclassified speakers by VSA differed greatly from those misclassified using the front vowel dispersion metric. Relative to front vowel dispersion, quadrilateral VSA demonstrated greater sensitivity to the presence of dysarthria in both moderately and severely impaired speakers and less sensitivity to mildly impaired speakers. This finding suggests that although the vowel metrics are significantly correlated (r = .67; see Appendix B for full correlation matrix), they may offer differential information regarding the speaker's communication disorder and perhaps should be used in tandem in such endeavors.

The formant centralization ratio has been proposed to be a more sensitive vowel space metric than triangular vowel space area in the identification of dysarthric vowel production, particularly for those with mild dysarthria (Sapir et al., 2010). This notion is not supported by the current data. Although the FCR tied with front vowel dispersion for least amount of healthy control misclassifications, with only one speaker being misclassified as dysarthric, it tied with triangular vowel space area for most dysarthric misclassifications (15 out of 45 dysarthric speakers were misclassified as healthy control). Further, 50% of the speakers diagnosed with mild dysarthria were misclassified as healthy control by the FCR. Thus, the FCR has good specificity but poor sensitivity. In addition, not only are triangular vowel space area and the FCR significantly correlated (r = −.79), but also the overlap of misclassified dysarthric speakers by the two metrics was substantial (approximately 73%). When considered with the fact that many other vowel metrics outperformed both the FCR and triangular vowel space area, it is likely that these metrics offer very similar, and perhaps not very useful, information in the classification of dysarthric speech.

[3]Although all vowels were sampled from connected speech, the phrases were read rather than spontaneously produced.

[4]It is important to note that the sample sizes of the severity groups were not equal. Speakers diagnosed with a moderate dysarthria (n = 25) greatly outnumbered those with mild (n = 6) or severe (n = 14) dysarthria. Therefore, we cannot rule out the possibility that the unequal sample sizes are responsible for the reduced classification accuracy of the moderately involved speakers.

A primary goal of this line of research is to identify objective acoustic metrics that are reliable indicators and prognosticators of dysarthria. Such metrics should be sensitive to the acoustic changes associated with even the mildest presentations of dysarthria. The classification data were examined to assess the abilities of each metric to identify the presence of dysarthria in mildly, moderately, and severely impaired speakers (see Table 4).[5] Front vowel dispersion was the sole metric that correctly identified 100% of mildly impaired speakers as dysarthric. As previously mentioned, 11 of the 12 healthy control speakers were correctly classified by the mean dispersion of the front vowels. Thus, this metric possessed good sensitivity and specificity in its ability to differentiate mildly impaired and unimpaired speakers. As previously mentioned, quadrilateral VSA accurately classified 83% of the mildly impaired speakers as dysarthric. However, four of the 12 healthy control speakers were misclassified as dysarthric. The classification accuracy of the mild speakers associated with the remaining variables ranged from 33% to 71%. In these cases, it was the correct classification of the more moderately to severely impaired speakers that appeared to escalate overall classification accuracy.

Overall, only the F2 slope metrics demonstrated significant between-group differences in the dysarthria subtype comparisons. However, classification accuracy by DFA was suboptimal, ranging from 44% to 53%. Results of the multiple comparison analyses revealed that only speakers with hypokinetic dysarthria are differentiated from those with ataxic or mixed flaccid-spastic dysarthrias by the F2 slope metrics. The F2 slope metrics were the only metrics that captured both spectral and temporal vowel information. This is an important factor to consider as the average speaking rate of the hypokinetic speakers, as reported in Liss et al. (2009), was on par with the control speakers and significantly faster than the speakers with dysarthria secondary to ALS, HD, and cerebellar degeneration. A post hoc analysis comparing mean F2 slope of all vowels and mean F2 slope of the most dynamic vowels associated with healthy control and hypokinetic vowel productions failed to reveal significant between-group differences. Thus, it is probable that the temporal information captured by these metrics of F2 slope, and not necessarily formant movement over time, is responsible for the significant ANOVA findings. Although some monophthongs are inherently more dynamic than others (e.g., Neel, 2008), it is important to note that movement of the second formant is more commonly studied in diphthongs or in consonant–vowel (CV) or vowel–consonant (VC) transitions (e.g., Y.-J. Kim et al., 2009; Weismer et al., 2001; Weismer & Martin, 1992). As previously mentioned, the F2 slope metrics used in this analysis were derived from monophthongs. It is possible that metrics capturing movement of the second formant in diphthongs and CV and/or VC transitions would demonstrate greater sensitivity to dysarthria.

[5]The speech severity of one speaker, AM3, was characterized as moderate–severe (see Table 1). For the purposes of this analysis, this speaker was included in the moderately impaired group.

In sum, these results support the taxonomical approach to dysarthria diagnosis as suggested by Weismer and Kim (2010). The vowel space metrics failed to demonstrate much value in classifying dysarthric speakers according to their speech diagnosis. Thus, the notion that vowel space compression represents a "perceptual similarity" uniting most, if not all, speakers with dysarthria is supported by the results reported herein. An important line of investigation for future work should define differences in the perceptual consequences of the vowel space compression relative to other acoustic manifestations of dysarthria.

Conclusion

Acoustic metrics that capture production deficits in dysarthria have the potential to be powerful and objective diagnostic and prognostic tools. Results of the present analysis support the use of acoustic metrics in the detection of dysarthria. However, in isolation, these results are not capable of informing an explanatory model of the communication disorder that dysarthria imposes. The critical question is how these acoustic metrics map to perceptual consequences. This step is addressed specifically in this work's companion piece (see Lansford & Liss, 2014).

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Appendix A

Stimulus Sets

Set 1	Set 2
account for who could knock	admit the gear beyond
balance clamp and bottle	assume to catch control
beside a sunken bat	attend the trend success
commit such used advice	butcher in the middle
constant willing walker	confused but roared again
embark or take her sheet	cool the jar in private
listen final station	done with finest handle
may the same pursued it	had eaten junk and train
mode campaign for budget	indeed a tax ascent
narrow seated member	kick a tad above them
her owners arm the phone	mate denotes a judgment
pooling pill or cattle	mistake delight for heat
push her equal culture	model sad and local
rode the lamp for teasing	rampant boasting captain
or spent sincere aside	remove and name for stake
technique but sent result	rocking modern poster
transcend almost betrayed	support with dock and cheer
unseen machines agree	vital seats with wonder

Appendix B

Intercorrelations of Dysarthric Vowel Metrics

Metric	1	2	3	4	5	6	7	8	9	10	11
1. Quadrilateral VSA	—										
2. Triangular VSA	.790**	—									
3. Lax VSA	.323*	.396**	—								
4. FCR	–.708**	–.790**	–.393**	—							
5. Mean dispersion	.791**	.723**	.459**	–.774**	—						
6. Front dispersion	.670**	.554**	.271*	–.585**	.623**	—					
7. Back dispersion	.611**	.434**	–.002	–.307*	.492**	.444**	—				
8. Corner dispersion	.804**	.614**	.227	–.675**	.809**	.677**	.592**	—			
9. Global dispersion	.823**	.737**	.418**	–.785**	.989**	.699**	.566**	.849**	—		
10. Average F2 slope	.414**	.216	.097	–.229	.355**	.460**	.461**	.348**	.408**	—	
11. Dynamic F2 slope	.546**	.317*	.132	–.312*	.479**	.485**	.541**	.481**	.526**	.885**	—

Note. VSA = vowel space area; FCR = formant centralization ratio.

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