

2012

## **Spectral analysis of stop consonants in individuals with dysarthria secondary to stroke**

Trescha S. Kay

*Louisiana State University and Agricultural and Mechanical College*

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SPECTRAL ANALYSIS OF STOP CONSONANTS IN INDIVIDUALS WITH DYSARTHRIA SECONDARY  
TO STROKE

A Thesis

Submitted to the Graduate Faculty of the  
Louisiana State University and  
Agricultural and Mechanical College  
in partial fulfillment of the  
requirements for the degree of  
Master of Arts

in

The Department of Communication Sciences and Disorders

By  
Trescha S. Kay  
B.S., University of Wisconsin Stevens Point, 2010  
May 2012

## ACKNOWLEDGEMENTS

I would like to take a moment to thank all the people who have contributed to the completion of my thesis. My advisor, Dr. Yunjung Kim, is by far at the top of this very long list. It was through Dr. Kim's patience and guidance that this thesis grew from a first year whim to a respectable scientific document. Her passion inspired me every step of the way and nurtured in me what I expect will be a lifelong love affair with research. I am eternally grateful to Meghan Collins for providing me with SLP contacts in the community. Without this list, I may still be stuck with only one participant. I also need to thank the SLPs in the Baton Rouge area who put up with my persistent emails asking them to check their caseloads for clients who fit my criteria. I would like to thank my committee members, Dr. Janna Oetting and Dr. Neila Donovan, for their time and effort to toward this project.

My parents were unbelievably supportive throughout this process. My mom was always just a phone call away, helping me through the hardest moments of the writing process. And though my dad isn't one to calm a frazzled grad student with long heart-to-heart conversations, I always felt his support and love in the calming silences of my calls home. Thank you both for everything you have done for me. Thank you to my brother and sister for being there for me and pretending to be interested in my research. I'm so very glad to be stuck with good people like you. And finally: my Charlie. Thank you for the late night calls, the early morning texts, and the panicked excel questions. Thank you for believing in me. Thank you for supporting me. Thank you for loving me through this crazy time in my life.

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## ABSTRACT

Dysarthria refers to a group of neurogenic speech disorders which result in abnormal strength, speed, range, steadiness, tone, or accuracy of movements required for speech production. Although speech deficits of dysarthria are heterogeneous according to lesion sites and/or etiologies such as stroke, traumatic brain injury, cerebral palsy, Parkinson's disease (PD), "imprecise consonants" has been known as one of the most prominent and frequently occurring features of dysarthria, which subsequently contributes to decreased speech intelligibility.

The present study points out the paucity of acoustic data on consonants produced by speakers with dysarthria, especially by spectral analysis, and reports four spectral moment analysis results on word initial stop consonants in six individuals with dysarthria and six age and gender matched healthy individuals. Each participant was asked to say a series of single words with a carrier phrase and a set of sentences. The initial 40ms of each single word was analyzed using TF32 to find the spectral moment values.

Results suggest that the first spectral moment (M1) was the most useful in differentiating between the genders, healthy vs. dysarthria, and place of articulation, which is consistent with previous studies. This moment revealed that individuals with dysarthria have higher values compared to healthy individuals, which indicates that this speaker group tends to have a more anterior constriction for stop production. Along with this fronting pattern, the M1 ratios between adjacent stops were reduced for the speakers with dysarthria, which indicates reduced acoustic contrast for stop production. However, no correlation was found between the perceptual speech intelligibility estimates and the spectral characteristics.

## INTRODUCTION

### 1.1 Dysarthria: Definition, Prevalence, Etiologies

Dysarthria refers to a group of neurogenic speech disorders which result in abnormal strength, speed, range, steadiness, tone, or accuracy of movements required for speech production (Darley, Aronson, & Brown, 1969; Duffy, 2005). These abnormalities result from injury to the central or peripheral nervous system and can result in weakness, spasticity, incoordination, involuntary movements, or abnormal muscle tone. Dysarthria accounts for 54% of acquired neurogenic disorders (Duffy, 2005). Etiologies such as stroke, traumatic brain injury, cerebral palsy, Parkinson's disease (PD), amyotrophic lateral sclerosis (ALS), multiple sclerosis (MS), and medications are known to cause dysarthria (American Speech-Language Hearing Association [ASHA], 2011). Speech symptoms of dysarthria (types and severity of dysarthria) depend on the affected neuropathophysiology, such that similar abnormal patterns of speech are expected within a given neurological disease and severity level (Darley, Aronson, & Brown, 1969a, 1969b; Kent & Kim, 2003).

### 1.2 Research Questions

'Imprecise consonants' is one of the only perceptual features that has been reported to occur across all types of dysarthria. However, surprisingly few acoustic data have been reported on consonants, especially stop consonants, except for one temporal parameter, voice onset time. Understanding the abnormal pattern of stop consonants would provide a better guide for therapy, differential diagnosis, and the nature of speech intelligibility deficits. This is especially true when considering of the potential impact of stop consonant production on speech intelligibility. Stop consonants account for 29% of all consonants so they make a considerable contribution to speech (Kent & Kim, 2008). In addition, Kim, Kent, and Weismer (2011) noted that imprecise



consonants would not classify a specific type of dysarthria unless research showed that the nature of the imprecision was unique to each dysarthria type. In recognition of the lack of acoustic data on dysarthria and the importance of stop characteristics on speech intelligibility and differential diagnosis of dysarthria, this study intends to answer three questions:

1. Is there a difference in the spectral characteristics of stop consonants between individuals with dysarthria and healthy individuals?
2. Is the variance in place of articulation across voiceless stop consonants more restricted in individuals with dysarthria than healthy individuals?
3. Is there a correlation between the perceptual estimate of speech intelligibility and the spectral information of stop consonants?

We hypothesize that there will be a significant difference between the spectral analyses of word initial stop consonant productions of the dysarthric and control groups and that individuals with dysarthria have a more restricted range of placement for stop consonants than healthy controls. We also expect a positive correlation between the perceptual estimate of speech intelligibility and the spectral analysis of stop consonants in the dysarthric group based on previous studies where spectral templates were discussed to function as acoustic cues for stop discrimination.

## LITERATURE REVIEW

### **2.1 Speech Characteristics of Dysarthria**

Our current knowledge about speech characteristics of dysarthria is primarily based on the classic studies by Darley, Aronson and Brown (1969a, b). They obtained speech samples from 212 patients who had one of seven medical diagnoses which resulted in dysarthria. From these speech samples, the authors were able to identify five distinct types of dysarthria: flaccid, spastic, ataxic, hypokinetic, and hyperkinetic each of which corresponds to its underlying neuropathology. They also described mixed dysarthria as resulting from multiple lesions to the central or peripheral nervous system and therefore causing multiple types of dysarthria to co-occur. Since this study, Duffy (1995) has extended the classification system with two additional types of dysarthria: unilateral upper motor neuron and type undetermined.

For this classification process, 38 dimensions of speech disturbances in seven categories (pitch, loudness, vocal quality, respiration, prosody, articulation, overall) may be detected (See Table 1 for 38 dimensions). These “dimensions” and “clusters (a group of dimensions characterizing each type of dysarthria)” are still used for clinical identification of dysarthria type in the form of the Mayo Clinic rating system. For example, flaccid dysarthria secondary to cranial or spinal nerve damage is known to exhibit speech disturbance clusters of hypernasality, imprecise consonants, breathiness (continuous), monopitch, nasal emission, audible inspiration, harsh voice quality, short phrases, and monoloudness (Duffy, 2005).

### **2.2 Perceptual Approach**

Duffy (1995) suggested three approaches to assessing the dysarthrias; perceptual, acoustic, and physiologic, although perceptual analysis has been the most commonly used

Table 1. 38 Dimensions of speech disturbances described by Darley, Aronson, & Brown (1969).

<b>Category</b>	<b>Dimension</b>
Pitch	Pitch level
	Pitch breaks
	Monopitch
	Voice tremor
Loudness	Monoloudness
	Excess loudness variation
	Loudness decay
	Alternating loudness
	Loudness level (overall)
Vocal Quality	Harsh voice
	Hoarse (wet) voice
	Breathy voice (continuous)
	Breathy voice (transient)
	Strained-strangled voice
	Voice stoppages
	Hypernasality
	Hyponasality
	Nasal emission
Respiration	Forced inspiration-expiration
	Audible inspiration
	Grunt at end of expiration
Prosody	Rate
	Short phrases
	Increase of rate in segments
	Increase of rate overall
	Reduced stress
	Variable rate
	Prolonged intervals
	Inappropriate silences
	Short rushes of speech
	Excess and equal stress
Articulation	Imprecise consonants
	Prolonged phonemes
	Repeated phonemes
	Irregular articulatory breakdown
	Distorted vowels
Overall	Intelligibility
	Bizarreness

method for description, evaluation, and differential diagnosis of dysarthria (Simmons & Mayo, 1997). An obvious benefit of using these perceptual methods is the elimination of costly tests or equipment. All of the aforementioned methods can be performed with a stop watch and a well-trained ear.

The majority of evaluations and assessments of dysarthria frequently administered are perceptual-based. The Frenchay Dysarthria Assessment (Enderby & Palmer, 2008) assesses nonverbal structure and function, patient reports, and speech characteristics to provide a comprehensive view of the patient's strengths and weaknesses for speech and non-speech acts. This assessment relies on examiner observation to determine the severity of deficit on the required tasks. Another dominant assessment is the Assessment of Intelligibility of Dysarthric Speech (AIDS) (Yorkston & Beukelman, 1981). This assessment provides quantified estimates of patients' intelligibility. Speakers with dysarthria are recorded saying a series of single words and sentences which vary in length from 5 to 15 words. Intelligibility data is obtained by having an unfamiliar listener transcribe their interpretation of the recording and comparing this to the original stimuli.

As previously mentioned, the Mayo Clinic rating system is still used to assist clinicians in perceptual assessment of clients. A survey of 100 speech language pathologists provided insight into the use of and attitudes towards the Mayo Clinic rating system. Simmons and Mayo (1997) performed a telephone survey of SLPs who had experience in diagnosing and treating individuals with dysarthria. The survey found that 60% used the Mayo Clinic rating system. An additional 18% of respondents reported using a descriptive approach similar to the Mayo Clinic rating system in their differential diagnosis. When asked to describe how helpful a diagnosis is in the development of treatment plans using a scale of 1.0-10.0, the median rating was 7.0. The

participants were also asked to rate on a scale of 1.0-10.0 the difficulty of differential diagnosis of dysarthria. The median response was 6.0, but 37% of responses were 7.0 or 8.0. This research demonstrates how heavily clinicians rely on perceptual analysis when diagnosing and treating dysarthria, but also how difficult they feel perceptual analysis of dysarthria is.

Since its genesis, some authors have pointed out the limitations of the use of the Mayo Clinic rating system. Gerratt, Till, Rosenbek, Wertz, and Boysen (1991) noted that because of the reliance solely on perceptual assessment this system could be detrimental to accurate differential diagnosis. It has also been suggested that the Mayo Clinic rating system was designed as a descriptive tool rather than a diagnostic assessment (Kent, 1994). An article by Kent (1996) described some of the limitations of auditory-perceptual assessment in speech language pathology. He specifically noted in reference to the Mayo Clinic rating system that the 38 attributes were not scaled with equal reliability and that there may be inter-judge variability in the descriptions of each disorder. Kent also brought up the point that judges may have a harder time using a multidimensional scale, such as the Mayo Clinic rating system. To counteract the undesirable lack of reliability of auditory-perceptual assessment, Kent suggested that the use of instrumental analysis in conjunction with perceptual rating could provide a more reliable diagnosis.

Despite its dominance, the validity of perceptual judgments has also been evaluated in several studies (Fonville, van der Worp, Maat, Aldenhoven, Algra, & van Gijn, 2008; Van der Graaff et al., 2009; Zyski & Weisiger, 1987). For example, a study by Fonville, van der Worp, Maat, Aldenhoven, Algra, and van Gijn (2008) found that only 35% of responses correctly classified type of dysarthria. Van der Graaff et al. (2009) similarly found participants were able

to correctly identifying only 41% of the samples. Zyski and Weisiger (1987) had slightly better results, with participants able to identify dysarthric speech samples with 56% accuracy.

Prior research has recommended an acoustic approach to differential diagnosis as a supplement to clinical perceptual approaches. Its advantages over a perceptual approach have been documented including that 1) the results are not affected by the listener, 2) it provides objective measures which can be compared to normative data, and 3) it enables clinicians to examine articulatory behavior in a non-invasive way (Kent & Kim, 2003; 2008). If acoustic data can pinpoint the specific detrimental behavior, it would be helpful to design a more individual-oriented therapy (Kim, Weismer, Kent, & Duffy, 2009).

### **2.3 Acoustic Approach**

Prior literature on acoustic characteristics of dysarthria has attempted to find a more objective means by which to characterize dysarthria type or determine the severity of impairment (Kent, Kent, Weismer, Martin, Sufit, Brooks, & Rosenbek, 1989; Ackermann & Hertrich, 1997; Morris, 1989; Kim, Weismer, Kent, & Duffy, 2009; Kim, Kent, & Weismer, 2011). Apparently some acoustic parameters were preferred as a means of identifying characteristics of certain forms of dysarthria or establishing a set of acoustic predictors of speech intelligibility.

For example, voice onset time (VOT) is one of the most frequently studied acoustic variables in speech and/or language disorders. VOT refers to the time interval between the time beginning of a consonant and the vowel onset (Ackermann & Hertrich, 1997). Furthermore, researchers have found VOT patterns vary across various types of dysarthria. Ackermann and Hertrich (1997) examined the VOT of eight ataxic adults and ten healthy control subjects. They found a typical contrast between the VOT of voiced (/d/) and voiceless (/t/) consonants in the healthy control group. In the ataxic study group, the authors found that as the severity of the

dysarthria increased, the contrast between voiced and voiceless consonant VOT decreased. Morris (1989) studied VOT in the voiceless consonants /p/, /t/, and /k/ in individuals with flaccid, spastic, ataxic, and hypokinetic dysarthria. This study found a shorter VOT when compared to normative data for these phonemes in all participants. Morris's (1989) study was also able to note a difference in VOT between some of the types of dysarthria. He reported that participants with flaccid or ataxic dysarthria had a significantly more variable VOT than the participants with hypokinetic or spastic dysarthria. Morris (1989) also noted that participants with flaccid or ataxic dysarthria had significantly longer VOT for the phoneme /t/ than the participants with spastic dysarthria.

F2 slope is another acoustic parameter that has been studied in individuals with dysarthria. Kim, Weismer, Kent, and Duffy (2009) examined 40 participants with dysarthria (20 with Parkinson's disease and 20 with CVA) compared to five control speakers. The participants with dysarthria varied in type and severity. This study found that F2 slopes were shallower in subjects with Parkinson's disease or CVA than healthy control subjects. The shallower F2 slope indicated slower movement of the oral mechanism in the subjects with dysarthria when compared to the normal F2 slopes. This study also examined the relationship between the reduced F2 slope and speech intelligibility. The authors found that out of six stimulus words used; only two had a significant relationship to speech intelligibility. They also reported no difference in the data collected from participants with Parkinson's disease and those who had had a stroke. In a more recent study, Kim, Kent, and Weismer (2011) reported a significant relationship between F2 slope and speech intelligibility. This study examined six stimulus words in 107 dysarthric participants representing several types of dysarthria. They found that as speech

intelligibility decreased, so did F2 slopes. But again, this study was unable to find a significant difference in F2 slopes between different types of dysarthria.

Finally, Kent et al. (1989) examined F2 slopes in individuals with dysarthria. The researchers recorded 35 individuals with dysarthria (25 male and 10 female) secondary to amyotrophic lateral sclerosis (ALS) and 30 healthy controls (15 male and 15 female) saying 12 words chosen for their various F2 trajectories. Kent et al. obtained moderately high correlations between speech intelligibility and F2 slopes for both the men and women groups. He also was able to demonstrate an overall higher F2 slope in the healthy control subjects than the ALS subjects.

Spectral analysis of speech, as opposed to temporal analysis, examines the changes in amplitude and frequency of speech signals over a period of time (Hixon, Weismer, Hoit, 2008). Spectral analysis of stops has been conducted for individuals with dysarthria primarily as a way to examine their production of fricatives. For example, Tjaden and Turner (1997) conducted a study on the spectral properties of fricatives in individuals with ALS. Seven individuals, three females and four males, with ALS and seven healthy controls matched for age and gender participated in the study. The participants were asked to read a passage three times, using a slow, habitual, and fast speaking rate. The passage contained 14 initial /s/ and 14 initial /ʃ/ phonemes. The samples obtained were split into four 10ms moments for analysis. The second through fourth moments did not provide any significant differences between the groups. The first moment spectral analysis showed the ALS females had lower coefficient than the healthy controls for the /s/ phoneme and the male ALS speakers had a higher /ʃ/ coefficient than the healthy male controls. The difference in coefficients indicated a structural difference in production of the fricatives. Particularly, the authors noted that the difference in the females'



production of /s/ could be due to “more posterior constriction, a wider or longer constriction, reduced flow through the constriction, or some combination of these factors” (p. 1366).

Dromey (2003) used spectral analysis to explore the relationship between long term average spectral (LTAS) measures and perceived intelligibility severity. He used LTAS measures to compare ten men with hypokinetic dysarthria secondary to Parkinson’s disease with ten healthy controls. The subjects were recorded sustaining the phoneme /a/ for three seconds, reading the first nine sentences of the Rainbow Passage (Duffy, 2005), and speaking for 30 seconds on a topic of their choice. Perceptual speech intelligibility ratings were obtained from five undergraduate students rating the first two sentences from the Rainbow Passage recordings. Researchers found a significant difference between the intelligibility ratings of the participants with dysarthria and the healthy controls. They were also able to identify a significant difference in the LTAS between the two study groups. Dromey noted the spectral analysis of speaking and vowel prolongation appeared to distinguish between the study groups more clearly than other phonatory measures.

Tjaden, Sussman, Liu, and Wilding (2010) more recently conducted a study intended to further evaluate positive results found by Dromey in 2003. 39 speakers (10 with Parkinson’s disease [PD], 14 with multiple sclerosis [MS], and 15 healthy controls) were recorded reading the Grandfather Passage (Duffy, 2005). SLPs were asked to perceptually rate the intelligibility of the recordings. These intelligibility ratings were then compared to the LTAS measures. A partial correlation, ranging from 0.16-0.53, was found between the LTAS measures and intelligibility ratings. There was, however, no difference between the LTAS measures of the study and healthy control groups. The authors noted that these results were in direct contrast to

the results found by Dromey (2003). They also questioned whether the PD and MS participants actually had dysarthria.

Although spectral measures of stop consonants have been unstudied in the dysarthric population, stop consonants have qualities that are particularly interesting for their impact on intelligibility. ‘Imprecise consonant’ is a common feature across all types of dysarthria, and that stops are frequently-occurring consonants in many languages including American English. American English stops are categorized into three cognates according to the place of articulation (labial, alveolar, velar) and into two cognates according to the manner of articulation (voiced vs voiceless). While a good deal of data has been reported for the latter by examining VOT distributions across voiced and voiceless stops, it is surprising that very little data exists for the former. Blumstein and Stevens (1979) were able to identify invariant acoustic properties of the place of articulation in stop consonants. They used three spectral templates, diffuse-rising, diffuse-falling, and compact to classify stop consonants with 80% accuracy. From these results, they further hypothesized that the auditory system is designed to detect these invariant acoustic properties to assist in decoding speech signals.

While spectral analysis of stop consonants has not been examined in the dysarthric population, it has been used with some success in research with phonologically disordered children. Forrest et al. (1990) compared the spectral analyses of the phonemes /t/ and /k/ in the initial position of words in four children with phonological disorders and four normally articulating children. All of the children with phonological disorders perceptually produced /t/ for /k/ in all word positions. The children were recorded producing a list of target words using the carrier phrase, “I can say.....” Spectral analysis was able to differentiate between /t/ and /k/ in the normally articulating children with 82% accuracy but was unable to identify a difference

in the productions of the children with phonological disorders. A later study by Forrest, Weismer, Elbert, and Dinssen (1994) performed spectral analysis on the productions of /t/ and /k/ in three groups of children (one normally articulating group and two groups with phonological disorders). The second group had mastered the production of /t/ and /k/ in all word positions while the third group was able to produce those phonemes in only the initial position. All groups were again asked to produce a list of target words using the carrier phrase, "I can say...." Spectral analysis was able to differentiate between the phonemes /t/ and /k/ with 82% in the first and second groups of children and accuracy dropped to 69% in the third group. The third group of children was then given speech therapy twice a week for the phonemes until generalization with 90% accuracy occurred. The children were then retested and found that the accuracy of classification by spectral analysis between the target phonemes had increased to 74%.

These studies used spectral analysis of stop consonants to provide further information about the acquisition of phonemes in children. Researchers were able to demonstrate the children's limited phonological knowledge through the decreased ability to differentiate between the spectral analyses of selected consonant productions (Forrest, Weismer, Hodge, Dinssen, & Elbert, 1990). In addition, the researchers were able to demonstrate an increase in the children's phonological knowledge by comparing the spectral analysis of the phonemes pre- and post-treatment (Forrest, Weismer, Elbert, & Dinssen, 1994). It is possible that spectral analysis of stop consonants may be used with equal success with dysarthric populations. As Tjaden and Turner (1997) showed a difference in the structural production of fricatives through spectral analysis, so may it be possible to demonstrate a difference in the productions of stop consonants.

The current study will conduct moment analysis on the voiceless stop consonants /p/, /t/, and /k/. Spectral moment analysis treats the spectrum as a distribution of numbers and computes

parameters that describe the central tendency, dispersion, tilt and peakiness of the set of numbers by using a reference of normal distribution shape (Figure 1). Mean (M1) is the average of all the numbers in the distribution, and variance (M2) indicates the degree to which those numbers are dispersed about the mean. Skewness (M3) means the degree of tilt of the distribution to the right or left of center, and kurtosis (M4) refers to the extent to which the distribution is peaked or flat.

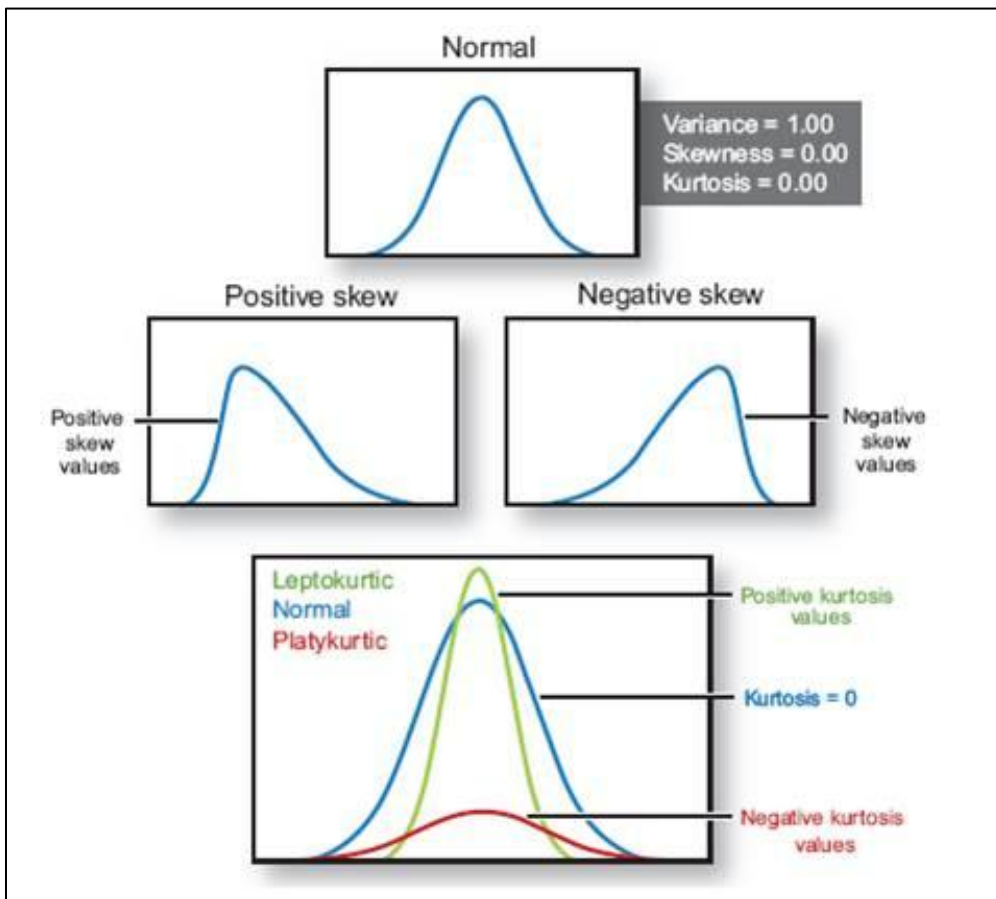


Figure 1. Distribution curves illustrating a normal curve (top graph), curves showing skewness (middle two graphs), and kurtosis (bottom graph) (Hixon, Weisner, & Hoit, 2008).

## METHODS

This study was a standard group comparison that sought to document the spectral characteristics of stop consonants produced by individuals with dysarthria secondary to stroke and healthy individuals. In other words, this study aimed to examine 1) the differences between the groups, and 2) if so, which phonetic context and analysis revealed these differences.

Approval from The Louisiana State University (LSU) Institutional Review Board for the protection of human subjects was obtained prior to enrollment of participants and data collection. Informed consent was obtained from each participant prior to data collection. Confidentiality of all participants' identifying information and data collected was ensured through the use of a password protected computer.

### **3.1 Participants**

Participants included six individuals with dysarthria resulting from stroke and six healthy individuals matched for age and gender. All participants were between the ages of 44 and 88. Participants in the study group (DYS) were diagnosed with dysarthria secondary to stroke, as confirmed by the Frenchay Dysarthria Assessment (Enderby & Palmer, 2008), absence of apraxia of speech as demonstrated by the Apraxia Battery for Adults-Second Edition (ABA-2) (Dabul, 2000), and no other neurological disorders. Presence of aphasia was not an exclusionary criterion, but rather the presence and severity was documented through the use of the picture description task of the Western Aphasia Battery-Revised (WAB-R) (Kertesz, 2007). The scoring of the picture description is scored 0-10, 0 meaning the participant not able to produce any words, 10 meaning normal, non-aphasic speech. The healthy control group (HC) consisted of participants who self-reported a healthy status and no history of stroke or other neurological disorders. Participant characteristics are summarized in Table 2 and Table 3.

Table 2. DYS participant information

Participant	Age in Years	Sex	Race	Time Post Stroke	Frenchay	ABA-2	WAB-R	DME Score
DYS1	46	F	African-American	12 months	Moderate	3-none 1-moderate	9	63
DYS2	71	M	Caucasian	14 months	Mild	3-none 1-mild	10	75
DYS3	60	M	African-American	6 weeks	Mild	3-none 1-mild	6	72
DYS4	44	F	African-American	2 months	Mild	4-none	5	54
DYS5	88	M	Caucasian	2 weeks	Mild	3-none 1-mild	10	81
DYS6	67	F	Caucasian	3 weeks	Mild	4-none	10	101

Table 3. HC participant information

Participant	Age in Years	Sex	Race	DME Score
HC1	49	F	Caucasian	173
HC2	74	M	Caucasian	151
HC3	59	M	Caucasian	97
HC4	45	F	African-American	179
HC5	89	M	Caucasian	139
HC6	66	F	Caucasian	171

An additional group of seven participants was recruited for the listening task. These participants were recruited from the LSU undergraduate Communication Disorders program. The only criterion for the participants is that they have normal hearing as established through self report.

### 3.2 Stimuli

The stimuli were three sets of five single syllable words with the stop consonants /p/, /t/, and /k/ in the syllable- and word- initial position. The full words lists are provided in Table 4 below. Each word was produced with a carrier phrase, “I can say...”, which was used for

spectral moment analysis. In addition to these word sets, participants were asked to say a set of five sentences. These sentences were: 1) “The cat had five kittens,” 2) “Cover and chill until serving time,” 3) “He told the patient to be careful,” 4) “Put them in a coat or jacket pocket,” and 5) “They really don’t do the job on my drains.” The sentences vary in length from five to nine words and were taken from the Assessment of Intelligibility of Dysarthric Speech (Yorkson, Beukelman, 1981) to use for perceived speech intelligibility ratings.

Table 4. Spectral analysis stimuli

Top	Pop	Cop
Tool	Pool	Cool
Tub	Pub	Cub
Tan	Pan	Can
Tick	Pick	Kick

### 3.3 Procedure

#### Speakers

The DYS group first completed selected sections of the ABA-2 (sections 2A, 2B, 3B, and 5) (Dabul, 2000), the full Frenchay Dysarthria Assessment (Enderby & Palmer, 2008), and the picture description of the WAB-R (Kertesz, 2007). Then the DYS and HC groups both were recorded saying each stimulus word with the carrier phrase and the sentences three times. The words and sentences were randomized and provided in written form for the participants to read. In one case (DYS4), the stimuli were spoken by the examiner and the participant repeated the stimuli. This participant had visual difficulties which prevented them from accurately reading the stimuli. All data were collected using an AKG microphone or a Tascam DR-07MKII and saved directly into a Dell Optiplex 745 computer with a 44.1 kHz sampling rate and 16-bit quantization. The speech samples were then analyzed using the program TF32 (Milenkovic, 2001).

## Listeners

Three sentences were selected from each speaker. These sentences were then provided to the LG group in randomized order for a speech intelligibility rating. The LG group rated the intelligibility of the speech samples using a direct magnitude estimates system (DME) (Weismer & Laures, 2002). DME is a method of perceptual ratio scaling in which an observer assigns a numerical estimate of the sensory magnitudes associated with a set of stimuli (Gescheider, 1976). DME was originally designed for physical stimuli (e.g. brightness), but recently has been used for the scaling of complex stimuli such as speech signals, especially in speech intelligibility. The LG subjects were provided with a reference sample which represented 50. They then rated the next five speech samples as compared to the reference sample. The standard mid-range reference sample was reintroduced every five speech samples to remind the LG participant what the reference was. Five samples were randomly selected to be rated twice to establish intra-rater reliability.

### **3.4 Acoustic and Statistical Analysis**

Spectral analysis of the phonemes /p/, /t/, and /k/ was performed using the program TF32 (Milenkovic, 2001). The initial 40ms window from the burst of the stop consonant was used to generate the spectrum display. Figure 2 is an example of the images that were obtained through spectral analysis. Based on the spectrum display provided, four M values (M1: mean, M2: variance, M3: skewness, M4: kurtosis) were compared across subjects by means of three-way ANOVA to analyze the difference between the phonemes and speaker groups. Regression analysis was also performed to examine the relationship between spectral moment values and perceived speech intelligibility ratings. Grand means, representing mean estimate of intelligibility, for each speaking participant were obtained from the data collected in the listening



task. Inter-rater reliability was established by randomly selecting a sentence from each speaking participant and comparing the scores across the listening participants.

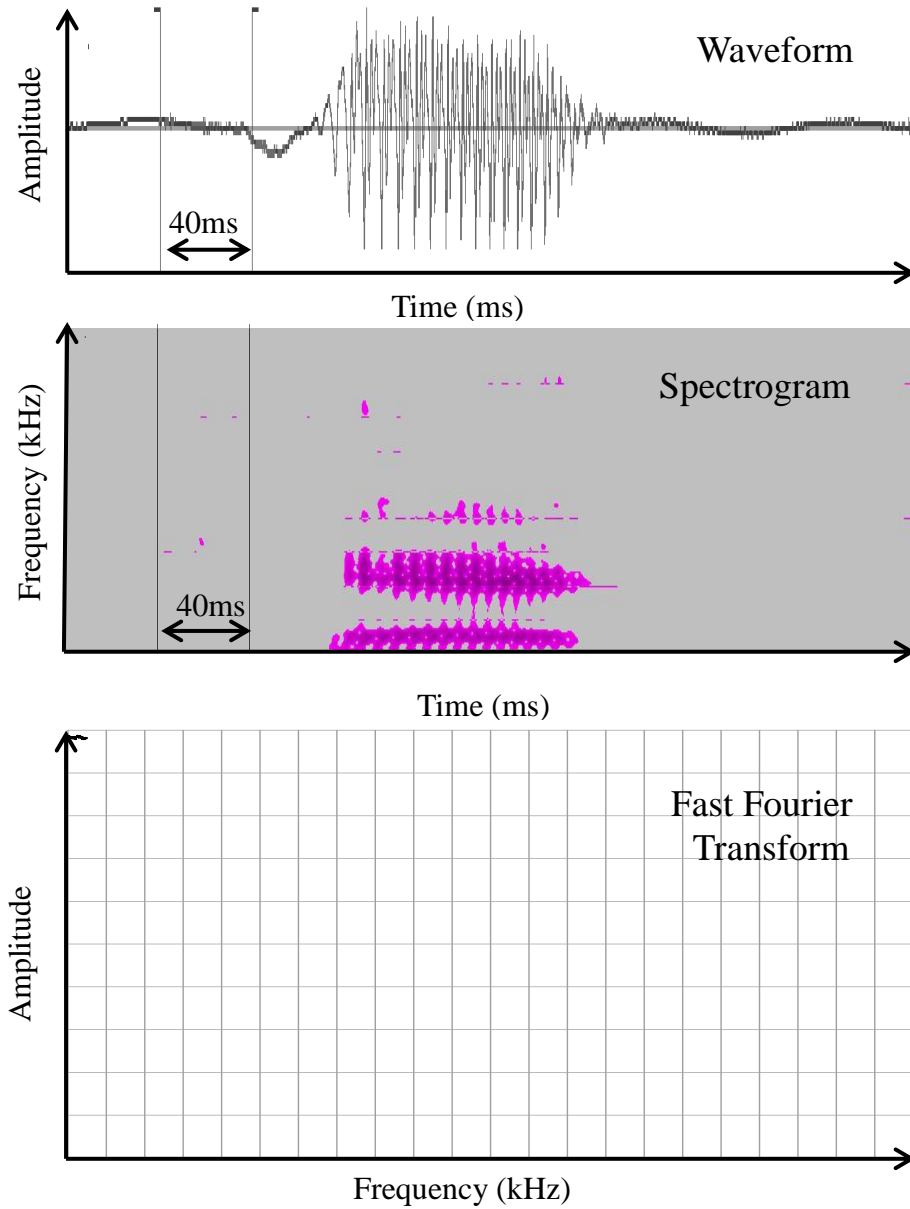


Figure 2. Analysis examples of “kick” produced by an 89 year old healthy male speaker. Waveform, spectrogram, and fast fourier transform (FFT) (from top to bottom). FFT was obtained from the 40ms window from the burst of stop.

## RESULTS

The results of this study will be reported according to the three research questions introduced previously.

### **4.1 Differences in the Spectral Characteristics of Stop Consonants between Individuals with Dysarthria and Healthy Individuals**

Previous to this study, there had been no direct investigation into the gender effect on spectral moments. However, given the potential difference between female and male speakers reported by Tjaden and Turner (1997), and preliminary data obtained from healthy speakers, , gender was also considered an independent variable. Therefore, three-way ANOVAs were conducted for each of the spectral moments to examine the effect of gender, healthy vs. dysarthria, and place of articulation on moment values. The relationships between the independent variables (gender, healthy vs. dysarthria, and place of articulation) were judged to be significant if the alpha value (sig.) was less than 0.05. Table 5 summarized the mean and standard deviations for each phoneme, spectral moment, gender, and healthy vs. dysarthria.

In M1 (mean), there was a main effect for gender,  $F(1, 521) = 34.868, P < .001$ , healthy vs. dysarthria,  $F(1, 521) = 35.514, P < .001$ , and place of articulation,  $F(2, 521) = 51.132, P < .001$ . There was a significant interaction between the effects of gender and healthy vs. dysarthria,  $F(1, 521) = 5.841, P = .016$ , gender and place of articulation,  $F(2, 251) = 8.017, P < .001$ , healthy vs. dysarthria and place of articulation,  $F(2, 251) = 20.182, P < .001$ , and gender, healthy vs. dysarthria, and place of articulation  $F(2, 251) = 3.538, P = .030$ . Females had significantly higher M1 values than males in the alveolar ( $P < .001$ ) and velar placements ( $P = .002$ ) by 1.62 kHz and .83 kHz, respectively. There was no difference between the genders

Table 5. Mean (standard deviation) of spectral moments separated by healthy vs. dysarthria, gender, and place of articulation

		Parameter	/p/	/t/	/k/
Dysarthria	Female	M1	8.019 (2.229)	10.487 (0.999)	9.143 (1.767)
		M2	4.096 (0.709)	3.251 (0.629)	4.132 (0.745)
		M3	0.354 (0.718)	0.108 (0.770)	0.192 (0.671)
		M4	0.410 (1.626)	1.047 (1.656)	0.204 (1.600)
	Male	M1	7.967 (1.657)	8.928 (1.530)	7.980 (1.394)
		M2	4.157 (0.716)	3.680 (0.647)	3.833 (0.770)
		M3	0.150 (0.523)	0.175 (0.467)	0.155 (0.612)
		M4	-0.033 (0.918)	-0.212 (0.811)	0.217 (1.459)
Healthy	Female	M1	6.377 (1.409)	8.352 (0.936)	9.222 (1.629)
		M2	4.248 (0.633)	2.580 (0.363)	4.020 (0.909)
		M3	0.818 (0.363)	0.774 (0.458)	-0.132 (0.686)
		M4	0.438 (1.670)	0.819 (1.098)	0.288 (1.828)
	Male	M1	6.096 (1.509)	7.586 (1.782)	8.728 (2.756)
		M2	4.455 (0.504)	3.417 (0.608)	4.179 (0.775)
		M3	0.887 (0.491)	0.888 (0.727)	0.243 (1.100)
		M4	0.441 (1.315)	1.244 (3.269)	0.886 (2.768)

in the bilabial placement ( $P = .544$ ). DYS group had significantly higher M1 values than the HC group in the alveolar ( $P < .001$ ) and bilabial placements ( $P < .001$ ) by 1.31 kHz and 1.76 kHz, respectively. There was no difference between the groups in the velar placement ( $P = .121$ ). According to Tukey post hoc tests, the alveolar phoneme had a significantly higher frequency than the bilabial phoneme by 1.5 kHz. The velar phoneme was also significantly higher than the bilabial by 1.6 kHz.

In M2 (standard deviation), there was a main effect for gender,  $F(1, 521) = 15.523$ ,  $P < .001$ , and place of articulation,  $F(2, 521) = 108.588$ ,  $P < .001$ . There was a significant interaction between the effects of gender and healthy vs. dysarthria,  $F(1, 521) = 8.158$ ,  $P = .004$ , gender and place of articulation,  $F(2, 251) = 12.536$ ,  $P < .001$ , and healthy vs. dysarthria and place of articulation,  $F(2, 251) = 13.248$ ,  $P < .001$ . DYS females had higher M2 values than HC females by .21 ( $P = .039$ ) but there was no similar significance between the

males ( $P = .203$ ). The DYS group had significantly greater values for the alveolar position ( $P = < .001$ ) by .47 but the HC group's values in the bilabial position were greater by .23 ( $P = .034$ ). Males had significantly higher M2 values than the females in the alveolar placement ( $P = < .001$ ) by .63 but there were no differences between the genders in the bilabial ( $P = .203$ ) or velar ( $P = .506$ ) placements. According to Tukey post hoc tests, the bilabial phoneme had a significantly higher frequency than the alveolar phoneme by 1.0 kHz. The bilabial phoneme was also significantly higher than the velar phoneme by 0.20 kHz. The velar phoneme was had a significantly higher frequency than the alveolar phoneme by 0.82 kHz.

In M3 (skewness), there was a main effect for healthy vs. dysarthria,  $F(1, 521) = 44.313$ ,  $P = < .001$ , and place of articulation,  $F(2, 521) = 21.680$ ,  $P = < .001$ . There was a significant interaction between the effects of gender and healthy vs. dysarthria,  $F(1, 521) = 4.312$ ,  $P = .038$ , and healthy vs. dysarthria and place of articulation,  $F(2, 251) = 19.106$ ,  $P = < .001$ . The HC group had significantly higher M3 values than the DYS group in the alveolar placement ( $P = < .001$ ) by .69 and the bilabial placements ( $P = < .001$ ) by .60. There was no difference in the velar placement ( $P = .245$ ). There was no significant difference between the genders in place of articulation. According to Tukey post hoc tests, the bilabial phoneme had a significantly higher value than the velar phoneme by 0.44 kHz. The alveolar phoneme was significantly higher than the velar phoneme by 0.37 kHz.

In M4 (kurtosis), there was a main effect for healthy vs. dysarthria,  $F(1, 521) = 7.010$ ,  $P = .008$ . There was a significant interaction between the effects of gender and healthy vs. dysarthria,  $F(1, 521) = 8.399$ ,  $P = .004$ . The HC group had significantly greater M4 values than the DYS group in the alveolar position ( $P = .030$ ) by .60. There was no significant difference in the other positions. Tukey post hoc tests revealed no significant differences.

Figure 3 demonstrates the differences in moment values between the HC and DYS groups across the place of articulation. M2 was not included as it was not found to be significant.

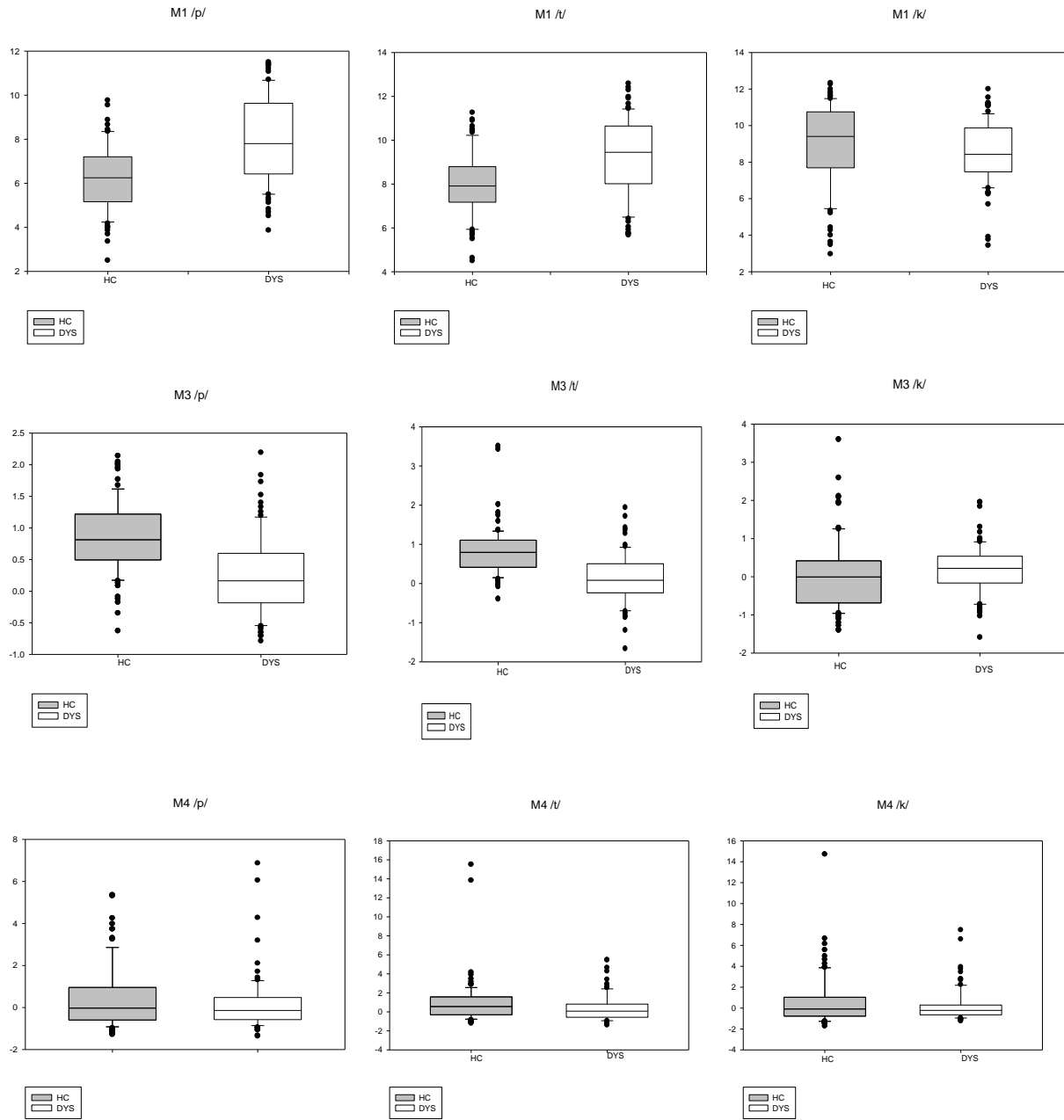


Figure 3. Differences between the HC and DYS groups' spectral moment values of the phonemes /p/, /t/, and /k/ in moments 1, 3, and 4.

## **4.2 Variance in Place of Articulation Across Voiceless Stop Consonants May be More Restricted in Individuals with Dysarthria than Healthy Individuals**

This research question was first approached by finding the ratios between the M1, M3, and M4 values obtained from words embedded in similar vocalic nuclei contexts (e.g.: pool, tool, cool). The ratios found were t/k and p/t, which is supposed to indicate spectral contrasts according to place of constriction. M2 was not analyzed as it was not found to be significant. Two-way ANOVAs were conducted to examine the effect of healthy vs. dysarthria and place of articulation on moment ratios. The relationships between the independent variables (healthy vs. dysarthria and place of articulation) were judged to be significant if the alpha value was less than 0.05. The results will be discussed by spectral moments.

In M1 (mean), there was a main effect for healthy vs. dysarthria,  $F(1, 346) = 13.777$ ,  $P < .001$  and place of articulation,  $F(1, 346) = 33.400$ ,  $P < .001$ . There was no significant interaction between the effects of healthy vs. dysarthria and place of articulation,  $F(1, 346) = 2.603$ ,  $P = .108$ . The p/t ratio was greater than the t/k ratio for both the DYS and HC groups by .30 ( $P < .001$ ) and .17 ( $P = .003$ ), respectively. This interaction is shown in Figure 4.

In M3 (skewness), no main effect was found for either healthy vs. dysarthria,  $F(1, 346) = .262$ ,  $P = .609$  or place of articulation,  $F(1, 346) = 2.906$ ,  $P = .089$ . There was no significant interaction between the effects of healthy vs. dysarthria and place of articulation,  $F(1, 347) = .101$ ,  $P = .751$ .

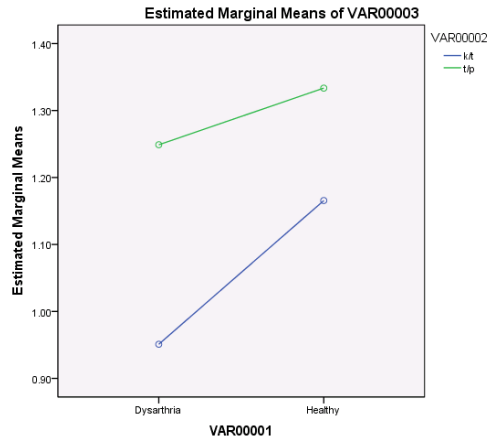


Figure 4. Interaction between the ratios t/k and p/t and healthy vs. dysarthria

In M4 (kurtosis), there was not a main effect for either healthy vs. dysarthria,  $F(1, 344) = .1078, P = .300$  or place of articulation,  $F(1, 344) = .598, P = .440$ . There was no significant interaction between the effects of healthy vs. dysarthria and place of articulation,  $F(1, 344) = 2.077, P = .150$ .

#### 4.3 Correlation between the Perceptual Estimate of Speech Intelligibility and the Spectral Information of Stop Consonants

Regression analysis was conducted to investigate the correlation between the perceptual speech intelligibility estimates and the spectral moment values. Because their data would not demonstrate a difference in severity, HC participants were not included in the regression analysis. The means of the phonemes were compared to the grand means obtained from the listening exercise.

No correlation was found for any articulatory position in any spectral moment. Figure 5 is an example of the correlational data obtained and shows that it is not significant.

#### 4.4 Reliability

To establish intra-rater reliability for acoustic analysis, two speaking participants were randomly selected and re-analyzed by the examiner. The correlation was .98.

Intra-rater reliability for the listening task was established by comparing the scores of the sentences presented twice. The intra-rater reliability of the listening participants was between

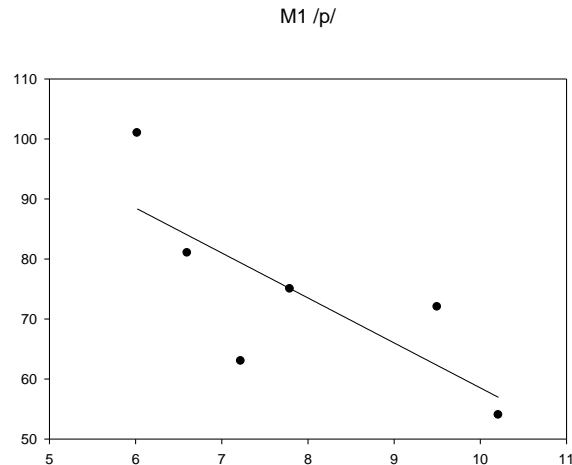


Figure 5. Regression analysis graph of the /p/ phoneme for M1.

.634 and .996 (mean = .900). Inter-rater reliability was established by selecting one sentence from each speaker and comparing the scores each listener assigned the speech sample. A Cronbach's alpha was performed to assess this reliability. The inter-rater reliability was found to be .83, which is considered satisfactory especially considering relatively low inter-rater reliability in similar studies (Kim et al., 2011).



## DISCUSSION

### 5.1 Application of Spectral Moment Analysis to Individuals with Dysarthria

The purpose of this study was to investigate and identify spectral characteristics of the speech produced by individuals with dysarthria who are frequently reported to exhibit articulatory imprecision, particularly in consonants. Despite the prominent impairments in consonant production of this population, very little research has been conducted on consonants, especially using spectral analysis, compared to relatively large amount of data from temporal analysis (e.g. voice onset time, frication duration). In addition, it is difficult to find normative data obtained from healthy speakers, although a couple descriptive studies have suggested that the spectral curve serves as an acoustic invariant for place of articulation of stop consonants (Blumstein and Stevens, 1979). This study is the first attempt to examine the spectral characteristics of stop consonants in individuals with dysarthria and its results suggest that spectral moment analysis provides useful information in describing acoustic abnormalities of speakers with dysarthria due to their articulatory impairments in stop production.

The relationship between the size of the oral cavity and resonant frequencies has been well established in prior research (Hixon, Weismer, & Hoit, 2008). As the size of the cavity in front of the constriction increases, the resonant frequency decreases, while as the size of the back cavity increases, the antiresonant frequency decreases. Based on this relationship, the results of the current study – the DYS group had higher first moment values than the HC group – indicate that the DYS group tended to have a more anterior position for the stop constriction than the HC group. Specifically, the DYS group's M1 values were higher than the HC group's values in both the bilabial and alveolar positions. Individually, all six DYS participants had higher M1 values for the /p/ phoneme than their HC matches. Four of the six DYS participants had higher M1

values for the /t/ phoneme. These results indicate a general tendency for individuals with dysarthria to have a more anterior placement for stop consonants than healthy individuals.

This ‘fronting’ pattern is interesting especially compared to previous studies on fricative productions (Tjaden and Turner, 1997), where speakers with ALS tend to have lower first moment values for /s/ than the healthy female group. They concluded this difference to be a result of a more posterior point of constriction, a wider or longer constriction, or a reduced flow through the constriction. Buder, Kent, Kent, Milenkovic, and Workinger (1996) also had similar findings in a single subject with dysarthria secondary to amyotrophic lateral sclerosis. They found that as the disease progressed, the first moment value of /s/ decreased. Buder et al. also concluded that this difference in frequency was due to a more posterior point of constriction.

The discrepancy between the findings of the current study and previous literature may be due to different underlying articulatory gestures required for fricative and stop production. Stop production is characterized by successive change in source and filter (Hixon, Weismer, & Hoit, 2008). In other words, stops are produced with successive time intervals (closure interval duration, burst, frication, and aspiration for voiceless cognates), of which sources and filters are continuously changing in a relatively short period of time. More complicating articulatory gestures may induce compensatory movements, such as fronting of constriction (Kaplan, 2010). Schwartz, Boe, Badin, and Sawallis (2011) discussed the idea that the speech mechanism is under evolutionary pressure to select gestures that are articulatorily efficient for communication. Once the mechanism is damaged and restrained by the effects of dysarthria, it is possible that the articulatory gestures which were once most efficient for communication are no longer viable options. In this case, the mechanism may need to evolve new gestures to achieve the desired sounds.

Another possibility for the greater M1 for the DYS group is incomplete oral closure for stops, which frequently occurs in speakers with dysarthria (also often in healthy speakers for velar stops). Friction on the acoustic surface is the aerodynamic consequence of an incomplete closure, which contributes to increasing resonant frequency.

Results of this study also found reduced moment ratio among bilabial, alveolar and velar stops. One would expect that due to the motoric limitations of dysarthric speech, the use of the oral cavity to shape speech production would be reduced, resulting in this more restricted articulatory placement. This restricted use of the oral cavity would be able to be quantified through finding the ratio of /p/ to /t/ and /t/ to /k/. This was indeed the finding of the present study. The DYS group consistently had smaller M1 ratios between adjacent stops than the HC group, which indicate that the DYS group exhibit reduced acoustic contrastivity across stops with different places of articulation.

The present study expected to find a significant correlation between the acoustic data and speech intelligibility estimates, given prior research that showed spectral change along with speech severity of dysarthria. For example, Buder, Kent, Kent, Milenkovic, and Workinger (1996) found this evolution in a longitudinal study of a single individual with dysarthria secondary to ALS. The authors described a perceptual decline of speech intelligibility and increasing severity of dysarthric symptoms, however, they did not quantify these observations in their paper. The current study did not find a significant correlation between any of the phonemes' spectral characteristics across all four moments and the speech intelligibility estimates, although some moment values reveal significant differences between the two speaker groups, probably because of the small number of participants.

As previously stated, it is not well understood how spectral moments can be used for identifying disordered speech or stop cognates with different place of articulation. This study supports the previous notion that some moments (e.g. M1) may be a useful acoustic parameter to examine consonant characteristics of speakers with dysarthria, but not all of them. (Forrest, Weismer, Milenkovic, & Dougall, 1988; Forrest, Weismer, Hodge, Dinnsen, & Elbert, 1990; Buder, Kent, Kent, Milenkovic, & Workinger, 1996; Tjaden & Turner, 1997). The first moment values were found to be the most significant while the second moment values were found to be mostly insignificant. This, along with the significance of M3 and M4, is consistent with previous studies. It should be mentioned that the second through fourth moments, by the nature the data they present, should not be treated autonomously from the first moment. In other words, because M2 represents a standard deviation, it requires M1 to provide a mean value from which it is derived. Nevertheless, M1 appears to be the most relevant spectral moment for clinical applications.

In summary, the first moment value (M1, mean) appeared to be promising in separating the DYS group from the HC group, which demonstrated the apparent fronting pattern of the DYS group. In addition, the ratios of M1 between adjacent stops were reduced, indicating less acoustic contrast (due to reduced articulatory distance) between stops with different places of articulation. The spectral characteristics found in this study were able to significantly differentiate between speakers with dysarthria and healthy speakers, however, no correlation was found between the perceptual speech intelligibility estimates and the spectral characteristics.

## 5.2 Limitations

Several limitations should be noted for this study. The participant groups were smaller than desired. Future studies should involve a larger number of participants to better control for unknown variables. Another possible limitation to this study is the time window for moment analysis. A 40ms window from the onset of the target phoneme has been used for spectral analysis based on a classic study by Forrest et al. (1988). However, given the rapid change in articulation process for stop production, probably a shorter time window would be preferred. In addition, the change of spectral moments over time, such as the trajectories from burst into vocalic nuclei, would be an interesting parameter to investigate in consideration the motoric issues which occur in the dysarthric population. .

It also should be noted that this study has different frequency ranges for spectral shape than other studies, which influenced the M1 values to be higher than those seen in previous studies (Forrest et al., 1988). This study utilized a higher sampling rate (44.1 kHz) and was not low-pass filtered, which provided 0-20 kHz frequency window for moment analysis, while previous studies used a sampling rate of 22 kHz, which produces a spectrum bandwidth of ~10 kHz. The difference between these two methods is that the present study collected data from spectra with a much wider frequency range. This increased amount of acoustic information likely skewed the spectral data, causing the increased values. This difference is believed to result in an atypical pattern across stops with different articulation places (increasing the M1 value as the placement moves posteriorly).

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## VITA

Trescha Kay was born in Manitowoc, Wisconsin, and raised in central Wisconsin. She graduated from D. C. Everest Senior High in 2003 and enrolled at the University of Wisconsin Stevens Point the following fall. Trescha spent a few semesters pursuing her childhood dream of becoming a music teacher before realizing that she did not want to spend the rest of her life teaching 10 year olds the difference between F and F#. Ms. Kay took several years off from school and worked full time as a file clerk for a large life insurance company. Her experience in the insurance business taught her several important life lessons: 1) Always document your work so no one can blame you when things go wrong, 2) Never let anyone walk away with your stapler, and, most importantly, 3) Unless you want to spend the rest of your life in a cube, you need a college degree. Trescha re-enrolled at UWSP, this time as a communication disorders major. Upon graduation in 2010, she packed up all her worldly belongings and fled the frigid Wisconsin winters for southern Louisiana. Ms. Kay began her master's degree at Louisiana State University in the fall of 2010 and will complete the program in the spring of 2012. Trescha has obtained a clinical fellowship position and will work toward her full certification as a speech-language pathologist.