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SPECTRAL/CEPSTRAL ANALYSIS OF VOICE QUALITY IN PATIENTS WITH PARKINSONS DISEASE

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SPECTRAL/CEPSTRAL ANALYSIS OF VOICE QUALITY IN PATIENTS WITH PARKINSON'S DISEASE

by

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Dedication

This dissertation is dedicated to my parents Ghazi Alharbi and Monera Alharbi , my husband Mohammed Alsharari, my daughter, and my mentors.

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We gratefully acknowledge the contributions of Debra Suiter, Ph.D. and Teresa Wolf, M.S. in providing LSVT and participating in the pre- post-evaluations.

PREFACE

Chapter 2 is in submission as a manuscript to Folia Phoniatrica et Logopaedica. Its authors are Ghadah G. Alharbi, Michael P. Cannito, Eugene H. Buder, & Shaheen N. Awan.

Chapter 3 is in preparation for submission as a manuscript to The American Journal of Speech-Language Pathology. Its authors are Ghadah G. Alharbi, Michael P. Cannito, Eugene H. Buder.

Abstract

Alharbi, G. Ghadah. Ph.D. The University of Memphis. June 2018. Spectral/Cepstral Analysis of Voice Quality in Patients with Parkinson's Disease. Major Professor: Eugene H. Buder, Ph.D.

The purpose of this dissertation was to determine whether Silverman Voice Treatment (LSVT) affects cepstral/spectral measures of voice quality in speakers with idiopathic Parkinson's Disease (PD). The first study investigated the effect of LSVT on cepstral/spectral measures of sustained /ɑ/ vowels to determine whether voice quality improves. Few studies have investigated the effects of LSVT on voice quality using acoustic measures, and none have used cepstral measures. The first study investigated the effect of LSVT on cepstral/spectral analyses of sustained /ɑ/ vowels produced by speakers. Sustained vowels were analyzed for cepstral peak prominence (CPP), CPP Standard Deviation (CPP-SD), Low/High Spectral Ratio (L/H SR), and Cepstral/Spectral Index of Dysphonia (CSID) using the Analysis of Dysphonia in Speech and Voice (ADSV) program. The study found both improved harmonic structure and voice quality as reflected in cepstral/spectral measures. Voice quality in connected speech is important because it is representative of how a typical individual communicates. Thus, the second study's goals were: first, to investigate the effect of LSVT on cepstral/spectral analysis of connected speech; and second, to compare cepstral/spectral analyses findings in connected speech with findings observed in sustained phonation. Another goal was to examine individual differences in response to treatment and compare them to individual changes observed in sustained phonation. The results demonstrated that CPP increased significantly following LSVT, indicating improved harmonic dominance as a result of treatment, and CSID decreased following LSVT, indicating a reduction of the overall severity in connected speech at the group level. Analysis of individual differences demonstrated that only four participants improved by at least one half Standard Deviation (SD) following treatment in CPP, CPP-SD, and CSID in both sustained phonation and connected speech tasks. Three showed a reduction in L/H SR in sustained phonation and only one showed an increase in L/H SR in connected speech. The other participants' improvement varied, but the majority demonstrated voice quality improvement in sustained phonation. The overall results indicated that CPP and CSID were strong acoustic measures for demonstrating voice quality improvement following treatment in both tasks connected speech and sustained phonation.

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Chapter 1: General Introduction

The proposed dissertation contains two research studies in response to LSVT in Parkinson's Disease (PD) speakers' voices using Analysis of Dysphonia in Speech and Voice (ADSV) for acoustic measurement. The first study investigated the effect of LSVT on cepstral/spectral analyses of sustained /ɑ/ vowels (Alharbi, Cannito, Buder, & Awan, in review). The second study's primary goal was to investigate the effect of LSVT on cepstral/spectral analyses of connected speech. The secondary goal was first to compare cepstral/spectral analyses findings in connected speech with findings observed in sustained phonation. Another secondary goal was to examine individual differences in response to treatment and compare it to individual changes observed in sustained phonation. These studies will be the first to examine the effect of LSVT on spectral/cepstral characteristics of voice in patients with PD.

The importance of this study rests in the fact that PD is ranked as the second most prevalent neurological disorder after Alzheimer's disease and its speech symptoms result in reduced intelligibility of speech (Darley, Aronson, & Brown, 1975; Duffy, 2013; Logemann, Fisher, Boshes, & Blonsky, 1978). PD speech symptoms are classified as hypokinetic dysarthria, which typically include monopitch, monoloudness, imprecise consonants, variable rate, breathy vocal quality, harsh voice quality, short rushes of speech, reduced loudness, inappropriate silences, and low pitch. Laryngeal endoscopic findings demonstrate hypo-adduction of the vocal folds (VF), bowing of the VF, supra-glottic tremor and/or hyper-function, and tremulous movements of the arytenoid cartilage (Hanson & Chuang, 1999).

Providing acoustic biomarkers for diagnosis of PD and monitoring of treatment-related changes needs objective acoustic voice analyses and measurement methods to show how individuals improve their voices following treatment. Acoustical analysis is also important for monitoring patients and providing feedback in a clinical setting (Rusz, Cmejla, Ruzickova, & Ruzicka, 2011). Cepstral/spectral analyses implemented in the ADSV is one such acoustic tool that is well-suited for the PD population because these measures do not depend upon automatic f_o cycle identification. These measures are applicable to both sustained vowels and connected speech, and are validated in the literature (e.g., Awan et al. 2016).

To date, the most effective treatment for speech disorders in PD is the behavioral therapy known as Lee Silverman Voice Treatment (LSVT®LOUD). LSVT is an intensive rehabilitation program that focuses on increased vocal loudness and high phonatory effort with the result of increasing vocal fold adduction (Ramig, Pawlas, & Countryman, 1995; Smith, Ramig, Dromey, Perez, & Samandari, 1995). LSVT has been shown to produce long-term voice improvements in speakers with PD, with effects lasting up to two years following treatment (Ramig, Sapir, Countryman, et al., 2001).

The lack of studies investigating the effect of LSVT on voice quality using acoustic measures motivated the first study (Chapter 2), which assessed the effect of LSVT on cepstral/spectral characteristics of sustained /ɑ/ vowels. Findings from the first study (Chapter 2) demonstrated an improvement in voice quality as reflected by cepstral/spectral results. Findings from the first study then motivated an additional analysis of data collected at the time of the first study (Chapter 3) to improve our understanding of how the same participants responded to LSVT in connected speech in comparison to sustained phonation.

Sustained vowels provide a relatively clear window into phonation produced without the potentially obscuring influences of supra-laryngeal articulation and prosodic variations (Dromey, 2003; Gerratt, Kreiman, & Garellek, 2016). The second study addresses the influence of supra-laryngeal articulation and prosodic variations on voice quality before and after voice therapy. Together these studies will enhance our understanding of acoustic changes in response to LSVT for two clinical speech tasks produced by speakers with PD.

It should be noted that the current studies did not assess the general efficacy of LSVT as a voice treatment for PD, although they did include a treatment component. The efficacy of

LSVT has been well established in the literature on speech and voice rehabilitation for several years based on two randomized blind control trials funded by the National Institutes of Health (Ramig, Countryman, Thompson, & Horii, 1995; Ramig & Dromey, 1996; Ramig, Sapir, Fox, & Countryman, 2001) and one privately funded delayed treatment onset randomized control trial (Halpern et al., 2012). In addition, numerous follow-up studies have been conducted to examine the response of specific experimental variables to LSVT, such as aerodynamic measures associated with phonation (Ramig & Dromey, 1996), perceived voice quality in connected speech (Baumgartner, Sapir, & Ramig, 2001), and vowel formant centralization (Sapir, Spielman, Ramig, Story, & Fox, 2007). Within this context, the present studies reported in this dissertation evaluated the responses to LSVT of selected acoustic spectral/cepstral measures, known to be predictive of the severity of voice quality disorders other than PD (Watts & Awan, 2011), within a sample of speakers with PD.

Chapter 2: Spectral /Cepstral Analyses of Phonation in Parkinson's Disease Before and After Voice Treatment

Introduction

More than 500,000 individuals in the United States have been diagnosed with Parkinson's Disease (PD), with prevalence of 1% of the population over the age of 60 and 5% prevalence occurring in individuals older than 85 (Reeve, Simcox, & Turnbull, 2014). Speech and voice difficulties develop during the course of PD in approximately 90% of patients (Sapir, Ramig, & Fox, 2013). The speech disorder associated with PD is hypokinetic dysarthria with characteristics that may include monopitch, monoloudness, imprecise consonants, variable rate, breathy vocal quality, harsh voice quality, short rushes of speech, reduced loudness, inappropriate silences, and low pitch, all of which result in reduced intelligibility of speech (Darley et al., 1975; Duffy, 2013; Logemann et al., 1978). However, the most distinctive speech characteristics are reduced loudness and monotone speech pattern (Dromey, 2003; Gentil & Pollak, 1995). Speech problems in PD typically affect voice first then later spread to articulation and fluency as the disorder progresses (Logemann et al., 1978) with higher incidence of voice disorders than articulatory disorders (Critchley, 1981). Laryngeal endoscopic findings demonstrate hypo-adduction of the vocal folds (VF), bowing of the VF, supraglottic tremor and/or hyper-function, and tremulous movements of the arytenoid cartilage (Hanson, Gerratt, & Ward, 1984).

A variety of treatments such as pharmacological, surgical, or traditional speech treatment have not proven to be effective for improving patients' speech and voice quality (Halpern et al., 2012). In contrast, Lee Silverman Voice Treatment (LSVT®LOUD), which is an intensive behavioral voice treatment developed for idiopathic PD (Halpern et al., 2012), has been shown to produce long-term voice improvements in speakers with PD lasting up to two years following treatment LSVT (Fox et al., 2006; Ramig, Sapir, Fox, et al., 2001). The primary effect of LSVT is an increase in vocal intensity (Cannito et al., 2012; Ramig, Countryman, et al., 1995). In addition, LSVT has been shown to significantly increase the maximum duration of sustained vowel phonation, maximum fundamental frequency range, habitual fundamental frequency, and fundamental frequency variability in speech (Ramig, Countryman, et al., 1995). LSVT also demonstrates positive perceptual results post treatment in patients' voice quality (Baumgartner et al., 2001) and intelligibility (Cannito et al., 2012).

Following LSVT, VF closure during phonation was observed to significantly improve (Smith et al., 1995). In addition, following LSVT, electroglottographic open quotient decreases while both subglottal pressure and the rate of airflow shut off increases (Ramig & Dromey, 1996). These changes should lead to increased dominance of harmonics in the acoustic spectrum during voicing (Titze, 1995).

To date only two acoustic single-case studies have examined spectral changes in sustained phonation produced by patients with PD following LSVT. Dromey et al. (2003) found a reduction in spectral noise and increased high frequency energy, with a reduction in spectral slope. Cannito et al. (2006) found that harmonic amplitude differences decreased post-LSVT, which is an indication of better VF closure during phonation, and also observed decreased spectral tilt in the regions of the F1, F2 and F3 (Hanson & Chuang, 1999). Furthermore, to the best of our knowledge, no studies have examined spectral/cepstral measures of dysphonia pre- to post-voice treatment in PD.

Voice acoustic measures may be classified into spectral/cepstral measures and traditional time-based acoustic periodicity measures, the validity of which depends on the voice signal type. Traditional time-based acoustic periodicity measures such as jitter (cycle-to-cycle variations in frequency), and shimmer (cycle-to-cycle variations amplitude) may only be useful in the description of Type I signals (nearly periodic signals) but are not valid for measuring Type 2 (signals which have quick qualitative changes such as subharmonics) or Type 3 (signals that are aperiodic) (Baken & Orlikoff, 2000; Titze, 1995). Due to the acoustical variability, dysphonia, and subharmonics seen in hypokinetic dysarthria, traditional time-based acoustic measures may not be appropriate (Dromey, 2003; Metter & Hanson, 1986). Thus, acoustic measures such as perturbation are vulnerable to methodological problems in application to PD because traditional time-based acoustic measures of phonatory perturbation depend on accurate identification of cycle boundaries (i.e. F_o determination) and onsets and offsets of cycles are especially difficult to locate if the voice periodicity is already unclear or perturbed (Hillenbrand, 1987).

Problems with F_o determination have been illustrated by the low correlations between acoustic and perceptual measures of sustained vowel phonation (Wolfe, Fitch, & Martin, 1997). In addition, Awan and Roy (2009) concluded that time domain measures like jitter and shimmer and some harmonics to-noise ratio (HNR) algorithm may similarly lack validity with increased dysphonia severity because of similar problems with F_o determination. The questionable validity of F_o tracker-based measures with dysphonic voices notwithstanding, it has been reported that jitter and mean F_o values were increased while intensity range was decreased in patients with PD compared with healthy participants (Goberman, Coelho, & Robb, 2002). Similarly, even with lack of validity, researchers applied the measure of jitter in participants with PD and reported that jitter was reduced in speakers with PD following LSVT (De Swart, Willemse, Maassen, & Horstink, 2003).

In contrast to traditional F_o perturbation measures, cepstral analysis (Noll, 1967) estimates the dominance of harmonics without identifying cycle boundaries. The cepstrum is a Fourier transformation of the log-power spectrum and may be used to quantify the degree to which harmonics resulting from the quasi-periodic oscillation of the vocal folds dominate the spectrum. Spectral/cepstral analysis of dysphonia incorporates both cepstral and spectral measures suited for dysphonia measurement in sustained vowel phonations and connected speech (Awan, Roy, Jetté, Meltzner, & Hillman, 2010). The measure of Cepstral Peak Prominence (CPP) provides an indication of the relative amplitude of the dominant harmonic in the voice signal. CPP standard deviation (SD) provides an indication of the CPP steadiness over time. The Low/High Spectral Ratio (L/H SR), which provides an indication of the dominance of spectral energy in the low frequency region (below 4kHz) versus energy in the high frequency region (above 4kHz), has also been reported to be a valid measure for assessment of various types of dysphonic voices in sustained vowels and continuous speech, with particular benefit in the categorization of breathy voices (Watts & Awan, 2011) (see Table 1 for descriptions of these measures). In addition, a composite index—the Cepstral Spectral Index of Dysphonia (CSID)—incorporates these measures in specific combinations suited for both sustained vowels, the CAPE-V sentences, and the Rainbow Passage. The CPP and the CSID have been useful for discriminating dysphonic voices from control voice samples, as well as pre- vs post-treatment voice characteristics in a variety of voice types (Awan, Solomon, Helou, & Stojadinovic, 2013; Gillespie, Dastolfo, Magid, & Gartner-Schmidt, 2014; Gillespie, Gartner-Schmidt, Lewandowski, & Awan, 2018; Lowell, Kelley, Awan, Colton, & Chan, 2012; Roy, Mazin, & Awan, 2014; Vogel et al., 2017; Watts & Awan, 2011).

Table 1

Measure Names and Descriptions

Measure Names	Descriptions
Cepstral Peak Prominence (CPP)	Mean difference between Cepstral Peak and regression fitted baseline
CPP Standard Deviation (CPP-SD)	Standard deviation of CPP measures across sample
L/H Spectral Ratio (L/H SR)	Mean ratio of energy below 4 kHz to energy above 4 kHz. Normal voice signal tend to have grater low frequency energy than high frequency energy (KayPentax, 2011).
Cepstral/Spectral Index of Dysphonia (CSID)	Result of a formula combining above measures predictive of perceived dysphonia, with different weightings for material and sex (Awan et al., 2013)

To date, few studies have looked at cepstral measures in patients with PD. Cepstral study of sustained phonation in untreated PD revealed reduced CPP in comparison to healthy participants (Kapoor & Sharma, 2011). The acoustic spectral voice characteristics of PD include abnormally increased spectral slope, which correlates with listeners' judgments of dysarthria severity and is indicative of breathiness and incomplete glottal closure (Dromey, 2003; Tjaden, Sussman, Liu, & Wilding, 2010). In treated PD, as previously discussed, reductions in the harmonic spectral slope and decreased spectral tilt have been observed in two case studies of persons with PD after LSVT (Cannito et al., 2006; Dromey, Ramig, & Johnson, 1995).

Since a number of previous studies have used spectral and cepstral measures (such as the CPP and CSID) to characterize hypofunctional voice samples, these measures may be valuable metrics for examining treatment related change in PD speakers. The present study expands upon previous work by incorporating cepstral measures which are suited to voice quality types seen in PD patients, and the physiologic changes that have been reported (Ramig & Dromey, 1996; Smith et al., 1995) predict that post treatment there should be changes in the spectrum, most specifically in harmonic structure. Converging evidence from various studies, while limited, also suggest that as voice intensity increases following LSVT, there should be systematic changes in the voice harmonic spectrum in speakers with PD. Therefore, it was the purpose of this study to perform the effect of LSVT on spectral/cepstral analyses of sustained vowels produced by speakers with PD. This information will enhance our understanding of how increased vocal intensity and glottal closure affect the spectral structure of phonation following LSVT.

The goals of this study were accomplished using cepstral/spectral analyses implemented in the ADSV software program (KayPENTAX, 2011). This study focuses on the effect of LSVT on cepstral/spectral measures of sustained vowels in order to provide a relatively clear window into phonation produced by speakers with PD, without the potentially obscuring influences of supralaryngeal articulation and prosodic variations (Dromey, 2003; Gerratt et al., 2016). Secondary goals of this study included evaluation of relationships among selected ADSV measures before and after treatment, given that these analyses have not been applied to a group of speakers with PD.

Given the voice-related physiological changes that have been previously reported following LSVT in PD, we hypothesize that following LSVT cepstral/spectral measures should demonstrate stronger harmonic structure (as reflected by increased CPP) resulting from treatment effects yielding more adequate glottal closure (Smith et al., 1995) during phonation. A reduction in CPP-SD also is predicted secondary to increased CPP. This in turn should lead to decreased overall dysphonia, as measured by CSID. Changes in L/H SR may be found, but given prior reports on spectral effects (Cannito et al., 2006; Dromey, 2003) and the default 4 kHz cutoff for the L/H ratio in ADSV (see Table 1 for descriptions of these measures), the direction of effects on this measure is unknown. Giving Cannito et al., (2006) and Dromey's (2003) findings and that the third formant (F3) is an important predictor for treatment related changes for three different vowels (Cannito et al., 2006), we predict that lowering the L/H SR cutoff to a region below F3 may best capture L/H SR reduction resulting from a stronger and louder voice following treatment.

Method

Participant information is listed in Table 2. Ten adults were included in this study (seven males and three females). Ages ranged between 52 and 81 years (mean = 67.5, SD = 8.37). Each participants' medical diagnosis was idiopathic PD, and the severity of PD was assessed by using the Mayo Clinic Rating Scales (Duffy, 2005). All were evaluated by an experienced ASHA certified speech language pathologist (SLP) to verify the presence of hypokinetic dysarthria with hypophonia before their enrollment in the project. A consent form approved by the Institutional Review Board of the University of Memphis was signed by each participant. Prior to enrollment in the study, laryngeal endoscopic examinations were completed by an otolaryngologist for all participants to rule out any VF pathologies that may contraindicate enrollment in a high-effort voice treatment. In addition, wave files were re-analyzed visually and perceptually to rule out any hyperfictional voice quality from the study. The enrolled participants were requested to continue following their regular anti-Parkinson medication schedules as prescribed by their physician throughout the study period. No additional speech or voice treatment besides LSVT was provided and no participants had received LSVT prior to the study.

Table 2

*Clinical Characteristics of Ten Speakers with Idiopathic Parkinson's Disease**

Participant	Sex	age	Years since diagnosis	medication	Single word Intelligibility Score**	Mayo Clinic Dysarthria Rating Scales
1	M	67	7	A, C	62%	Marked monopitch, monoloudnes, reduced loudness, audible inspiration, short phrases, increased rate, breathy voice (continuous), imprecise consonants; moderate reduced stress; mild alternating loudness and harsh voice
2	F	62	11	B	56%	Severe strained-strangled voice, voice tremor, voice stoppages, prolonged intervals; marked pitch breaks, monopitch, voice tremor, monoloudness, reduced loudness, harsh voice, reduced rate, reduced stress, imprecise consonants; moderate breathy voice (transient) and weak pressure consonants
3	M	77	6	B	40%	Severe monopitch, monoloudness, reduced loudness, breathy voice, increased rate, reduced stress, short rushes of speech, imprecise consonants, repeated phonemes, irregular articulatory breakdowns; marked harsh voice and palilalia
4	F	61	3	B	60%	Marked monopitch, monoloudness, reduced loudness, voice stoppages, increased rate (segments), Variable rate, short rushes of speech, prolonged phonemes, irregular articulatory breakdowns; Moderate breathy voice (transient), prolonged intervals, inappropriate silence, imprecise consonants

*:A=L-dopa, B = sinemet, C = requip, D = carbo/levodopa, E = amantadine, F = Mirapex, G = comtan, H = sinemet

**as measured by the *Assessment of Intelligibility for Dysarthric Speech*

Table 2 (continued)

Participant	Sex	age	Years since diagnosis	medication	Single word Intelligibility Score**	Mayo Clinic Dysarthria Rating Scales
5	F	81	23	D, E, F	50%	Severe monopitch, monoloudness, harsh voice, strained-strangled voice; marked reduced pitch Level, pitch breaks, increased rate, variable rate, imprecise consonants; moderate weak pressure consonants, repeated phonemes, distorted vowels
6	M	71	27	B, E	NA	Marked monopitch, monoloudness, reduced loudness, breathy voice (continuous), short phrases, inappropriate silences; moderated harsh voice; mild excess loudness variation, reduced stress, prolonged intervals
7	M	72	15	B, F, G	52%	Severe reduced pitch level and imprecise consonants; marked monopitch, monoloudness, reduced loudness, weak pressure consonants ;moderate alternating loudness and reduced stress; mild loudness decay and hoarse voice
8	M	52	3	F	62%	Marked monopitch and monoloudness; moderate reduced loudness, breathy voice (continuous), reduced stress; mild harsh voice, reduced rate, simple vocal tics
9	M	46	2	None	55%	Severe monoloudness; marked monopitch, moderate breathy voice (continuous), short phrases, reduced stress, inappropriate silence; mild harsh voice

*:A=L-dopa, B = sinemet, C = requip, D = carbo/levodopa, E = amantadine, F = Mirapex, G = comtan, H = sinemet
**as measured by the *Assessment of Intelligibility for Dysarthric Speech*

Table 2 (continued)

Participant	Sex	age	Years since diagnosis	medication	Single word Intelligibility Score**	Mayo Clinic Dysarthria Rating Scales
10	M	68	20	B	29%	Severe short phrases; marked monopitch, monoloudness, reduced loudness, breathy voice (transient), weak pressure consonants, reduced stress, short rushes of speech; moderate alternating loudness, variable rate, inappropriate silences, imprecise consonants, repeated phonemes, irregular articulatory breakdowns; mild prolonged phonemes

*:A=L-dopa, B = sinemet, C = requip, D = carbo/levodopa, E = amantadine, F = Mirapex, G = comtan, H = sinemet
**as measured by the *Assessment of Intelligibility for Dysarthric Speech*

Other than having the same diagnosis and no prior speech or voice treatments, the sample of speakers with PD recruited for this study was clinically diverse. Variable characteristics of the sample included the following: one participant who experienced bilateral deep brain stimulation (speaker 6), one participant had a history of bilateral pallidotomy (speaker 5), three participants used hearing aids (speakers 4, 5, and 8), one participant did not take anti-Parkinson medication (speaker 9), five participants were ambulatory (speakers 1, 2, 3, 7, and 8), two participants used walkers with assistance (speakers 4 and 5), and one participant was a wheelchair user (speaker 6). Prior to final analyses, acoustic data from speaker 7 were excluded due to severe vocal hyperfunction. Cepstral analysis has not been reported to be highly effective in the characterization of severely hyperfunctional, strained voices; (Awan, Roy, Zhang, & Cohen, 2016). Moreover, it was also questionable whether this participant was a viable candidate for LSVT. Participant histories revealed a wide range of years since diagnosis, and participants also presented with varying degrees of severity of PD and of dysarthria. Single word intelligibility (SWI) was measured by graduate students who found that SWI varied from 29% to 62% as measured by the *Assessment of Intelligibility of Dysarthric Speech* (Yorkston & Beukelman, 1984).

Each participant underwent standard LSVT administered by an ASHA certified SLP who was also a certified LSVT provider. All speakers enrolled in LSVT participated in a total of 16 sessions for four days a week for four weeks. Speech recordings were obtained on three different days within one week before and one week after LSVT. Each speaker was instructed to produce three repetitions of a sustained vowel /a/ holding out the vowel as steady and as long as she or he can. There were no cues for the participant to produce loud production during the pre- and post-treatment assessments. Multiple trials were obtained to examine potential variability of phonation during the recording sessions and to evaluate potential practice effects (Kent, Kent, & Rosenbek, 1987). Recordings were collected in a sound booth using a head mounted condenser microphone (AKG C420) with a flat frequency response below 10 kHz, positioned out of the breath stream and 4 cm from the corner of the speaker's lips (Titze & Winholtz, 1993). Signals were digitized directly to disc at a sampling rate of 44.1 kHz using Kay Elemetrics CSL 4300B hardware (KayElemetrics). Acoustic analyses were obtained using the KayPENTAX Analysis of Dysphonia in Speech and Voice (ADSV) software (KayPENTAX, 2011). Prior to ADSV, to approximate a 25 kHz standard for ADSV analysis and as traditionally used for CSID (Awan et al., 2010), signals were down-sampled to 22.05 kHz. Each vowel signal was excerpted from a longer file by trimming the onset of the vowel in accordance with ADSV protocol, as well as the offset of the vowel, to assure a 50 ms silent period before and after each production. Because extraneous noise could impact the results, trimming was also performed as needed to remove unwanted sections from an otherwise satisfactory capture such as coughs, throat clears, et cetera.

To reiterate, acoustic measures obtained via the ADSV program included Cepstral Peak Prominence (CPP), CPP Standard Deviation (CPP-SD), and Cepstral/Spectral Index of Dysphonia (CSID). The Low/High Spectral Ratio (L/H SR) measure was analyzed twice using two different frequency cutoffs. First, the ADSV default cutoff 4 kHz was used for both males and females to restrict the L/H SR into the region of the F1, F2, and F3. Second, the cutoff was adjusted to 2 kHz for males and 2.5 kHz for females to provide greater focus on the F1 and F2 regions of the spectrum (the adjusted values were chosen based on consulting the time-frequency analysis software (*TF32*) to confirm that the cutoff was right above F1 and F2 and below the F3).

Both intra- and inter-observer measurement reliability were calculated for 67% of sound files per participant productions by trained graduate students in a speech-language pathology program. For reliability assessments, all vowel signals were again segmented from the longer recordings and re-trimmed to include the silent period, then submitted review to the ADSV for analysis. For intra-analyst reliability, data were not reanalyzed until a 4-month waiting period had passed. Reliability was high for all selected ADSV measures of sustained vowels for both inter-analyst ($r > 0.90$, $p < 0.001$) and intra-analyst ($r > 0.90$, $p < 0.001$) comparisons. Participants' sustained vowels exhibited increased intensity (dB) from pre-to-post treatment, in keeping with expectations of LSVT (t (8) = -3.44 $p < 0.05$).

Data were analyzed for each of the four acoustic variables using a three-way repeated measures ANOVA. Within-participants variables were Treatment Period (Pre-T_x, Post-T_x), Recordings Days (days 1, 2, and 3 Pre-T_x and days 1, 2, and 3 Post-T_x), and Vowel Trials 1, 2, 3 within each recording day. In this study, the day effect was included in the model to assess whether the treatment effect exceeded day to day variability before and after treatment. An overall α-level = 0.05 was Bonferonni adjusted to 0.0125 for testing four acoustic variables. Inter-relationships among variables were evaluated with Pearson's r correlations among the four acoustic variables within participants averaged across trials and days within each pre-T_x period and post-T_x period (α-level = .01 due to the number of correlations). These correlations are of interest because the CPP is the primary contributer to the CSID (Awan et al., 2010). However, the correlation among these measures is not known for treatment effects for persons with PD, where we anticipate that the L/H SR component of CSID may operate differently than in normative populations.

Results

Table 3 provides the means and SDs for each measure obtained from the PD participants before and after LSVT, averaged across recording days. Results indicated that four acoustic variables demonstrated statistically significant differences from pre-to-post LSVT: CPP (F (1, 8) = 13.78, p= 0.006, η^2 = .63), CPP-SD (F(1, 8) = 10.32 , p= 0.012, η^2 = 0.56), adjusted L/H SR cutoff (F(1, 8) = 11.78 , p= 0.009, η^2 = 0.60), and CSID (F(1, 8) = 14.99, p= 0.005, η^2 = 0.65). L/H SR using the default 4kHz cutoff (F(1, 8) = 1.79, p= 0.217, η^2 = 0.18) did not differ significantly from pre-to-post treatment. There were no statistically significant main effects or interactions involving days or trials. Selected measures' data are depicted in Figure 1, and sample analyses are presented in Figure 2.

Table 3

Descriptive statistics summary for PD group before and after treatment:

Dependent Variables	Pre-LSVT	Post-LSVT
	Mean (SD)	Mean (SD)
CPP	9.96 (1.72)	12.35 (1.38)
CPP SD	1.60 (.49)	1.25 (.33)
L/H SR 4 kHz	36.47 (5.50)	34.60 (5.60)
Adjusted L/H SR	34.43 (6.12)	28.94 (5.05)
CSID	35.84 (13.80)	21.87 (10.18)

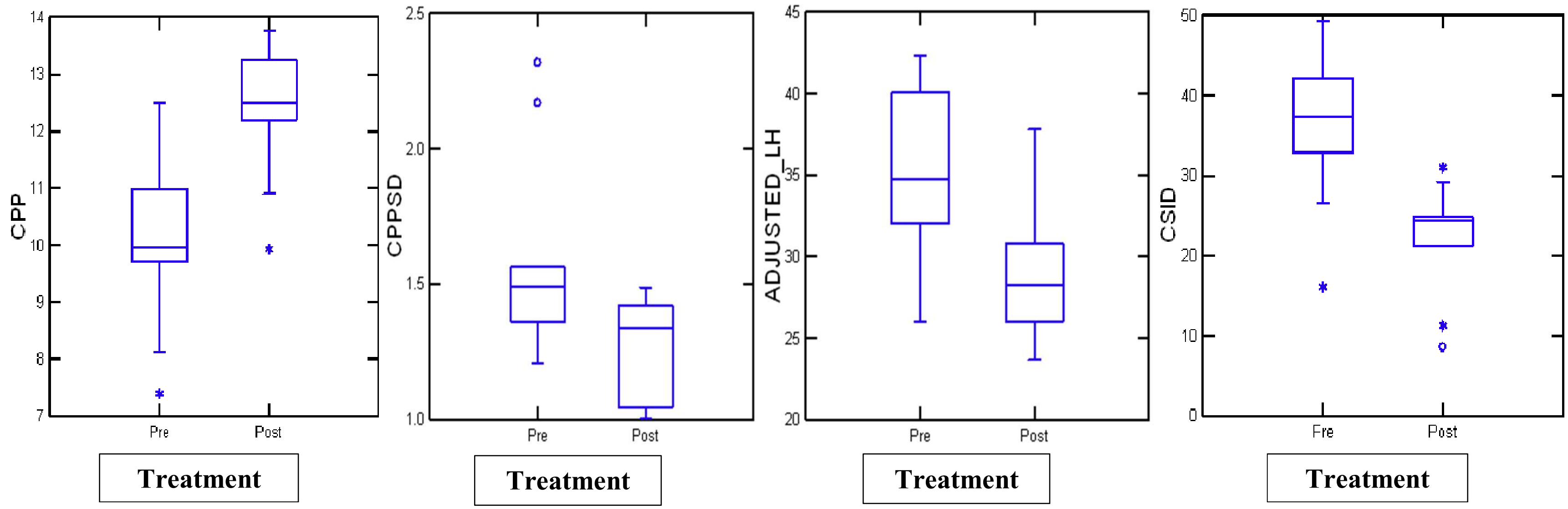

Figure 1. Box plot showing averaged pre-Tx and post-Tx values for CPP, CPPSD, Adjusted L/H SR, and CSID variables.

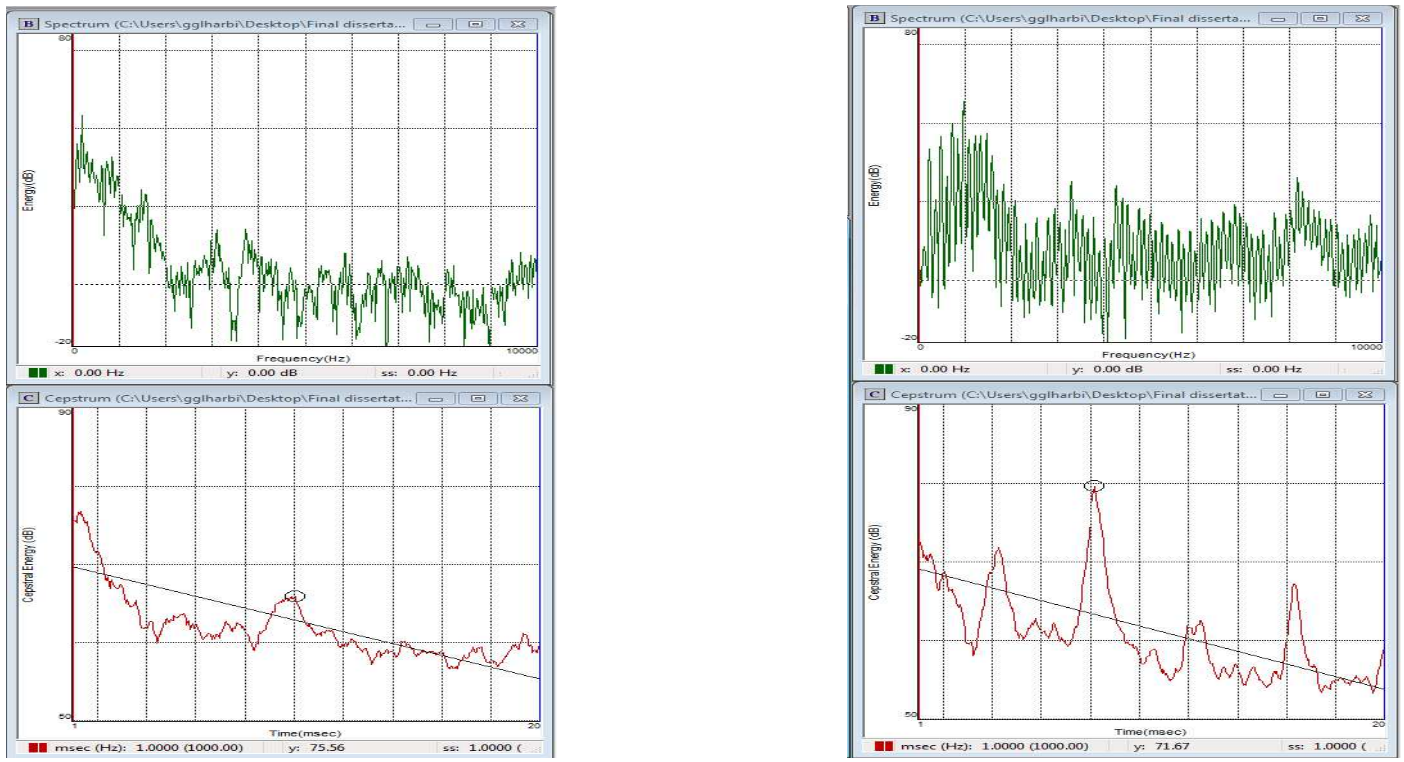

Figure 2: Sustained vowel production of PD participant#5 demonstrating increased harmonic structure and reduced spectral noise pre- to post-treatment (Top panels). Bottom panels demonstrate increased CPP from pre-to post-treatment. Pre-treatment CPP= 7.03, Adjusted L/H SR = 34.26, and CSID=51.304. Post-treatment CPP = 13.00, Adjusted L/H SR = 22.22 which indicated the high frequency energy increased following treatment, and CSID=30.08

Inspection of relationships among variables before LSVT demonstrated a strong negative correlation between CPP and CSID which was statistically significant (r = -0.869, p = 0.002). A strong positive correlation was observed between CPP-SD and CSID (r = 0.837, p = 0.005). In addition, CPP and CPP-SD demonstrated a strong negative correlation which was statistically significant (r = -0.708, p = 0.033) (See Table 4). Post LSVT, a significant negative correlation was observed between CPP and CSID (r = -0.756, p = 0.019). However, no other variables, including CPP, were significantly correlated after treatment (See Table 5).

Table 4

Pearson's r correlations for spectral/ cepstral acoustic variables pre-TX

		CPP Pre	CPPSD Pre	L/H pre	CSID pre
CPP Pre	Pearson Correlation	1	-.708*	-.066	-.869**
	Sig. (2-tailed)		.033	.865	.002
	N	9	9	9	9
CPPSD Pre	Pearson Correlation	-.708*	1	.014	.837**
	Sig. (2-tailed)	.033		.970	.005
	N	9	9	9	9
L/H pre	Pearson Correlation	-.066	.014	1	-.125
	Sig. (2-tailed)	.865	.970		.748
	N	9	9	9	9
CSID pre	Pearson Correlation	-.869**	.837**	-.125	1
	Sig. (2-tailed)	.002	.005	.748	
	N	9	9	9	9

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

Table 5

Pearson's r correlations for spectral/ cepstral acoustic variables Post-TX:

		CPP Post	CPPSD post	L/H post	CSID Post
CPP Post	Pearson Correlation	1	-.381	-.301	-.756*
	Sig. (2-tailed)		.312	.431	.019
	N	9	9	9	9
CPPSD post	Pearson Correlation	-.381	1	-.071	.642
	Sig. (2-tailed)	.312		.857	.062
	N	9	9	9	9
L/H post	Pearson Correlation	-.301	-.071	1	-.168
	Sig. (2-tailed)	.431	.857		.665
	N	9	9	9	9
CSID Post	Pearson Correlation	-.756*	.642	-.168	1
	Sig. (2-tailed)	.019	.062	.665	
	N	9	9	9	9

*. Correlation is significant at the 0.05 level (2-tailed).

Discussion

The primary purpose of this study was to examine the effect of LSVT on cepstral/spectral analyses to acoustically characterize PD voice quality. The findings demonstrated that CPP increased significantly following LSVT, indicating improved harmonic dominance as a result of treatment. These spectral changes are consistent with, and indirectly support, the findings of previous studies demonstrating increased glottal closure during phonation (Smith et al., 1995), increased subglottal pressure, and decreased EGG open quotient post LSVT (Dromey et al., 1995; Ramig & Dromey, 1996). In part, the present findings may reflect the sensitivity of CPP to variations in vocal loudness/intensity (Maryn, Roy, De Bodt, Van Cauwenberge, & Corthals, 2009). Awan et al. (2012) showed that CPP increases as vocal loudness increases in unimpaired speakers from soft to comfortable to loud phonation. However, in Awan et al. (2012) the mean difference in dB from quiet to comfortable was 6.25 dB and was associated with an increase in CPP of only 1.11 dB. In addition, the same study showed that the mean difference in mean dB from comfortable to loud was 6.37 dB and was associated with an increase in CPP of only 0.6 dB (the change from quiet to loud was a mean dB change of 12.62 dB and associated with a 1.71 dB increase in CPP). In the current study, the mean increase in sound level pre vs. post-treatment was 7.68 dB, and therefore the significant increase in CPP reported here probably was not due to increases in vocal loudness and intensity alone but most probably representative of improved vibratory characteristics and vocal quality. Prior to treatment there is decreased glottal closure resulting in atypically breathy phonation, even for soft voice which contributes to severely diminished harmonic structure. The increases of glottal closure and subglottal pressure post treatment alter vocal fold vibration yielding both increased periodicity and increased vocal intensity. Additional research is needed to explore the relationship between CPP and overall intensity in speakers with PD before and after treatment. The CPP has been described as the most powerful acoustic measure for dysphonia severity to date (Gaskill, Awan, Watts, & Awan, 2017; Maryn et al., 2009). Its large effect size in the present study underscores its value as a treatment outcome measure for speakers with PD. Increased CPP is also consistent with previous case studies that demonstrated improved spectral structure and decreased spectral tilt from pre-to-post LSVT (Cannito et al., 2006; Dromey et al., 1995).

CPP-SD was also observed to significantly differ pre-to-post treatment (see Figure 1). The significance of the CPP treatment effect and the significance of the CPP-SD suggest that the dominance of harmonic structure improved following treatment and its variability within sustained vowel productions reduced significantly as a result of treatment. CPP-SD is typically expected to be minimal for sustained vowels and the analysis indicated that the PD participants in the present study did reduce the variability of CPP after treatment compared to the pre-treatment levels.

The L/H SR did not significantly change after LSVT using the default cutoff of 4 kHz. Even though Watts & Awan (2011) reported that the L/H SR differentiated normal versus hypo-functional groups, this measure did not detect the treatment effect in PD speakers in the present study. One possibility for this finding is that spectral changes following LSVT only occurred at frequencies below the 4 kHz cutoff. Cannito et al. (2006) reported that there was upward frequency redistribution of harmonic energy after LSVT, above the second harmonic, primarily in the regions of F1, F2 and F3 (all below 4 kHz), which was associated with decreased spectral tilt. In addition, Dromey et al. (2003) found increased high frequency energy, with a reduction in spectral slope post LSVT. Another possibility is that the hypo-functional voices investigated by Watts & Awan (2011) exhibited greater degrees of breathiness than our participants with PD: high frequency turbulence of breathiness would account for a reduced L/H SR, but if the main effect of LSVT treatment was specific to the generation of stronger harmonic energy overall then it is possible this effect would not be seen in the L/H SR. This change in spectral energy distribution was particularly evident and statistically significant when the L/H ratio cutoff was reduced to restrict the L/H into the region of the F1, F2 and F3. The significance of the results after lowering the default cutoff (4 kHz) demonstrated the energy following treatment is redistributed into the higher frequency region of the spectrum following treatment consistent with Cannito et al. (2006) and Hanson & Chuang (1999).

Further studies are needed to replicate these findings with a larger data set and to extend ADSV analyses to phonation elicited at long term follow up post LSVT. It will also be of interest to directly compare present analyses with other harmonic spectral analytic techniques that also do not depend upon automatic F_o cycle identification in both sustained vowels and connected speech produced by individuals with PD.

Chapter 3: Spectral /Cepstral Analyses of Connected Speech in Parkinson's Disease as Compared with Sustained Phonation Before and After Voice Treatment

Introduction

Voice disorders associated with Parkinson's Disease (PD) were first described by James Parkinson in 1817: "His words are now scarcely intelligible," "The power of articulation is lost," "The speech was very much interrupted," "What words he still could utter were mono-syllables, and these came out, after much struggle, in a violent expiration, and with such a low voice and indistinct articulation, as hardly to be understood but by those who were constantly with him" (Parkinson, 1817, p. 24). This description demonstrates the laryngeal, respiratory, and articulatory impairments which have since been considered in a variety of perceptual, acoustic, and physiological studies of persons with PD (Baker, Ramig, Luschei, & Smith, 1998; Yorkston, 1996). Researchers have found that the most salient speech and voice characteristics of PD were related to phonatory impairment, with articulation being the second most affected speech subsystem (Logemann et al., 1978; Ludlow, Bassich, McNeil, Rosenbek, & Aronson, 1984).

Respiratory and phonatory deficits in a person with PD affect the production of speech, leading to problems with phrasing and intensity (Ludlow et al., 1984). Respiratory deficits may cause a reduction in vital capacity, a reduction in intraoral air pressure during consonant/vowel productions, and abnormal airflow (Ramig, Fox, & Sapir, 2007). Alternatively, it has been suggested that abnormal movements of both vocal folds (VFs) and the supra-laryngeal articulators may lead to atypical variation in airflow resistance, which may explain apparent abnormalities in respiratory function (Ramig et al., 2007). At the laryngeal level, hypo-adduction of the VFs, bowing of the VFs, supraglottic tremor and/or hyper-function, and tremulous movements of the arytenoid cartilage have been demonstrated endoscopically in individuals with PD (Hanson et al., 1984).

Studies investigating listener impressions of speech and voice characteristics in PD include decreased vocal intensity, decreased articulatory precision, mono-pitch, breathy or harsh voice quality in speech tasks (Lam & Tjaden, 2016), and less spectrally distinct consonants (Tjaden & Wilding, 2004). These are important factors that affect intelligibility (Baumgartner et al., 2001; Ferrand, 2001). Speech production studies in speakers with PD demonstrated deficits in oral closure for stop consonants, reduced range of articulator motion for diadochokinetic (DDK) tasks, deficits in the amplitude and velocity of lip and mandible movements, and slowed articulator movement during vowel production (Goberman & Coelho, 2002) and during speech tasks including oral reading of the first paragraph of the Rainbow Passage (Flint, Black, Campbell-Taylor, Gailey, & Levinton, 1992). It has been reported that speakers with PD tend to inappropriately produce acoustic energy during the stop gap of voiceless consonant (Kent, Weismer, Kent, Vorperian, & Duffy, 1999). In addition, slowness of articulation was indicated by a shallower second formant (F2) slope (Kim, Kent, & Weismer, 2011). At the supra-segmental level, more pauses and increases in fundamental frequency (F_o) with a reduction in its variability, reduced sound pressure levels (SPL), and rate abnormality have also been reported (Tjaden & Wilding, 2004).

A variety of treatments for PD such as pharmacological, surgical, or traditional speech interventions have not proven to be effective for improving patients' speech and voice quality (Halpern et al., 2012; Shimon Sapir et al., 2007). In contrast, the Lee Silverman Voice Treatment (LSVT®LOUD), which is an intensive behavioral voice treatment developed for idiopathic PD (Halpern et al., 2012), has been shown to produce long-term voice improvements in speakers with PD lasting up to two years following treatment LSVT (Fox et al., 2006; Ramig, Sapir, Fox, et al., 2001). The primary effect of LSVT is an increase in vocal intensity (Ramig, Countryman, et al., 1995). In addition, LSVT has been shown to significantly increase the maximum duration of sustained vowel phonation, maximum fundamental frequency range, habitual fundamental frequency, and fundamental frequency variability in speech (Ramig, Countryman, et al., 1995). LSVT also demonstrates positive changes in perceived voice quality (Baumgartner et al., 2001), acoustic harmonic structure of sustained vowels (Alharbi, Cannito, Buder, & Awan, in review) and intelligibility post-treatment in speakers with PD (Cannito et al., 2012).

Following LSVT, VF closure during phonation was observed to significantly improve (Smith et al., 1995). In addition, following LSVT, the electroglottographic open quotient decreased while both subglottal pressure and the rate of airflow shut off increased (Ramig & Dromey, 1996). Such changes lead to an increased dominance of harmonics in the acoustic spectrum during voicing in sustained phonation tasks (Alharbi et al., in review).

In voice quality assessments, it is important to assess connected speech and sustained vowels. However, many voice quality assessments are drawn from short vowel segments of sustained vowel tasks (Watts & Awan, 2015). Several reports have found that measurements obtained from connected speech in certain populations may better predict voice classifications such as age and gender, and voice disorders than measurements obtained from sustained vowels (Ma & Love, 2010; Maryn & Roy, 2012; Roy, Mauszycki, Merrill, Gouse, & Smith, 2007).

Even though connected speech has been found to better predict voice classification such as age and gender, and differentiating adductor spasmodic dysphonia from muscle tension dysphonia (Ma & Love, 2010; Roy et al., 2007), it is important to assess both tasks, connected speech and sustained vowels, because voicing behaviors differ for both connected speech and sustained phonation. Sustained vowels provide a relatively clear window into the balance between noise and periodicity related to glottal function or dysfunction without the potentially obscuring influences of laryngeal and supra-laryngeal articulation and prosodic variations (Dromey, 2003; Gerratt et al., 2016; Watts & Awan, 2015). Moreover, according to Awan et al. (2010), connected speech provides the clinician with information on how the patient's vocal parameters are controlled for communicative purposes and the severity of the voice disorder, Moreover, connected speech correlates better with perception of dysphonia than do sustained vowels. In addition, individuals with dysphonia perceive their dysphonia during connected speech to be more impaired than during vowel production (Watts & Awan, 2015).

The choice of assessment tasks remains controversial because dysphonia may be more prominent for different disorders during sustained phonation or during connected speech (Awan et al., 2013). Furthermore, we study connected speech because it tells us about phonation in the face of the potentially obscuring articulatory and prosodic features that are absent when using sustained vowels. Thus, both tasks are equally important to consider in assessment and evaluation of therapeutic outcomes.

Voice acoustic measures may be classified into spectral/cepstral measures and traditional time-based acoustic periodicity measures. Traditional time-based acoustic measures of phonatory perturbation depend on accurate identification of cycle boundaries for F_o determination. Such measures include jitter, shimmer and some algorithms for harmonic-to-noise ratios. Onsets and offsets of cycles are especially difficult to locate if the voice periodicity is already unclear or perturbed as with dysphonia (Hillenbrand, 1987). Thus, traditional time-based acoustic measures may not be appropriate for the analysis of PD due to the acoustical variability, dysphonia, and subharmonics seen in hypokinetic dysarthria (Dromey, 2003; Metter & Hanson, 1986). In addition, the characteristics that differentiate connected speech from sustained phonation, such as rapid pitch and loudness variations, noise production during consonant production and the short voicing segments in connected speech (Awan et al., 2010), increase errors in the time-based measures yielding invalid results for connected speech, especially with severely dysphonic speakers (Peterson et al., 2013).

In contrast to period-based measurement approaches, spectral/cepstral measures of dysphonia have been reported to be sensitive for quantifying the degree to which harmonics dominate the spectrum and therefore the strength of periodicity in the voice. These measures, however, do not rely on automated identification of cycle boundaries and are therefore not participant to the limitations noted for traditional period based techniques. In addition, cepstral measures have been validated for estimating dysphonia severity for a variety of phonation tasks (Awan et al., 2016; Awan et al., 2013; Gaskill et al., 2017). Moreover, the utility of these measures has been supported for differentiating typical and disordered voice production (Watts & Awan, 2011).

Spectral/cepstral analysis of dysphonia incorporates a number of useful acoustic voice parameters. Cepstral Peak Prominence (CPP) provides an indication of the relative amplitude of the dominant harmonic in the voice signal. CPP standard deviation (SD) provides an indication of the CPP variability over time. The L/H SR provides an indication of the dominance of spectral energy in the low frequency region (below 4 kHz) versus energy in the high frequency region (above 4kHz). L/H SR SD provides an indication of the L/H SR variability over time (KayPENTAX, 2011). In addition, a composite index—the Cepstral Spectral Index of Dysphonia (CSID)—incorporates these measures in specific combinations suited for sustained vowels, the CAPE-V sentences, and the Rainbow Passage (Watts & Awan, 2011) (see Table 6 for descriptions of these measures).

Table 6

Measure Names and Descriptions

Measure Names	Descriptions
Cepstral Peak Prominence (CPP)	Mean difference between Cepstral Peak and regression fitted baseline
CPP Standard Deviation (CPP-SD)	Standard deviation of CPP measures across sample
L/H Spectral Ratio (L/H SR)	Mean ratio of energy below 4 kHz to energy above 4 kHz. Normal voice signal tends to have greater low frequency energy than high frequency energy (KayPENTAX, 2011).
Cepstral/Spectral Index of Dysphonia (CSID)	Result of a formula combining above measures predictive of perceived dysphonia, with different weightings for material and sex (Awan et al., 2013)

In sustained phonation, a periodic signal is expected to represent a well-defined F_o and harmonic structure associated with steadiness and consistency in its quality, pitch, and loudness over time, which is indicated by high amplitude CPP. In contrast, dysphonic voice is characterized by its decreased CPP amplitude and associated with an increase in its variability over time. In connected speech, normal speakers tend to have an increased CPP variability over time due to their vocal mechanism transitioning between voice/voiceless consonant and the normal variation of pitch and loudness. In contrast, for dysphonic voices CPP tend to have decreased variability in connected speech over time. In sustained phonation, normal speakers tend to have a high L/H SR due to the concentration of the voice energy in the frequency region below 4 kHz while dysphonic voice tends to have a reduced L/H SR due to their high frequency energy above 4 kHz. In connected speech, normal speakers tend to have increased L/H SR variability over time due to their vocal mechanism transitioning between voice/voiceless consonants and the variation of pitch and loudness across phrases and utterances. On the other hand, dysphonic voices tend to have a decreased L/H Ratio variability in their connected speech over time (Awan et al., 2010)

The CSID uses different formulas to estimate the dysphonia severity for connected speech and sustained phonation. For oral readings of the Rainbow Passage, CSID predicts dysphonia severity from the second and third sentence because these two sentences are >5 seconds in duration, providing a sufficient sample for estimating the speaking F_o (Awan et al., 2016). The formula for calculating CSID for the spectral/ cepstral analysis (CPP, L/H SR, and L/H SR SD), incorporated into a multiple regression equation was reported in Awan et al. (2009):

$CSID_R = 154.59 - (10.39xCPP) - (1:08xSR) - (3.71x\sigma\ SR)$,

Where the $CSID_R$ is the Cepstral Spectral Index of Dysphonia computed from the Rainbow Passage, CPP is mean Cepstral Peak Prominence, SR is the L/H Spectral Ratio, and σ SR is the standard deviation of the L/H Spectral Ratio (Awan et al., 2009).

For sustained phonation, the formula for calculating CSID for the spectral/ cepstral analysis (CPP, CPP-SD, L/H SR, and L/H SR SD), incorporated into a multiple regression equation reported in Awan et al. (2009):

$CSID_V = 84.20 – (4.40 \text{ x } CPP) + (10.62 \text{ x } \sigma_{CPP}) – (1.05 \text{ x } SR) + (7.61 \text{ x } \sigma_{SR}) – (10.68 \text{ x } G)$

Where the $CSID_V$ is the Cepstral Spectral Index of Dysphonia computed from the Rainbow Passage, CPP is mean Cepstral Peak Prominence, σ_{CPP} is the standard deviation of the CPP, SR is the L/H Spectral Ratio, σ SR is the standard deviation of the L/H Spectral Ratio, and G is the gender variable (Male = 0; Female = 1).

Several authors have supported the use of spectral/cepstral measures in connected speech. Hillenbrand and Houde (1996) demonstrated that CPP strongly correlated with perceptual ratings of breathiness, which were obtained from the second sentence of the Rainbow Passage (Fairbanks, 1960). In addition, Heman-Ackah, Michael, and Goding (2002) demonstrated that cepstral peak measures exhibited the strongest correlations with overall dysphonia and breathiness ratings in continuous speech (using the second sentence of the Rainbow Passage) and in sustained vowel samples. Gillespie, Dastolfo, Magid, and Gartner-Schmidt (2014) concluded that L/H ratio and its SD may be an important outcome measure to track responses to surgical and behavioral intervention in patients with various voice disorders including vocal fold lesions, primary muscle tension dysphonia, vocal fold atrophy or unilateral vocal fold paralysis. Moreover, Awan, Roy, and Dromey (2009) concluded that spectral/cepstral-based measures are strong measures for assessing dysphonia severity in continuous speech (the 2nd and 3rd sentences Rainbow Passage), among the various voice types and severities seen in muscle tension dysphonia speech samples before and after treatment (Awan, Roy, and Dromey, 2009).

To date, few studies have looked at spectral/cepstral measures in patients with PD. Cepstral study of sustained phonation in untreated PD revealed reduced CPP in comparison to healthy participants (Kapoor & Sharma, 2011). In addition, low CPP and L/H ratio, and higher CSID were demonstrated in untreated PD in comparison to healthy participants (Byeon et al., 2016). The acoustic spectral voice characteristics of PD include abnormally increased spectral slope, which correlates with listeners' judgments of dysarthria severity and is indicative of breathiness and incomplete glottal closure (Dromey, 2003; Tjaden et al., 2010). In treated PD, reductions in the harmonic spectral slope and decreased spectral tilt have been observed in two case studies of persons with PD after LSVT (Cannito et al., 2006; Dromey et al., 1995). Furthermore, it was reported that CPP, L/H ratio, and CSID in sustained phonation improved significantly in sustained vowels following LSVT, and the L/H SR energy redistributed into the higher frequency region of the spectrum (Alharbi, Cannito, Buder, Awan, in review). To the best of the authors' knowledge, only one study has investigated spectral/cepstral characteristics of PD voice quality in the connected speech of untreated PD speakers. The study revealed a reduced CPP in comparison to healthy participants (Byeon, Jin, & Cho, 2016). Investigating CSID in connected speech will clarify how well this composite measure is suited for speakers with PD. Thus, specifying the spectral/cepstral characteristics of a specific population such as PD should build our understanding of how connected speech may improve in this population following voice treatment.

The primary goal was to study the effect of LSVT on cepstral/spectral analyses in connected speech for the purpose of understanding acoustic voice quality in a group of speakers with PD. Given that the cepstral/spectral measures have not been applied to the evaluation of the effect of voice treatment on connected speech in speakers with PD, the goals of this study were accomplished using cepstral/spectral analyses implemented in the ADSV software program. An additional goal was to compare descriptively the effect of task for the PD group as a whole, comparing cepstral/spectral analyses findings in connected speech with findings observed in sustained phonation (Alharbi et al., in review). Finally, due to the heterogeneous nature of speakers with PD, it was also of interest to examine individual differences in spectral/cepstral measures obtained from the connected speech and sustained phonation tasks after LSVT. This will provide a better understanding of how phonation with the inclusion of articulation and prosodic variations of connected speech may differ from the previously reported spectral/cepstral findings for sustained phonation within the same individuals.

Based on the findings from Alharbi et al., (in review), it was hypothesized that following LSVT, cepstral/spectral measures should demonstrate improved harmonic structure in connected speech, which will be reflected by an increased CPP. CPP-SD is expected to increase in connected speech following treatment. L/H SR is expected to increase because participants are expected to improve their consonant precision which will be reflected by the reduction of the high-frequency spectral noise (Gillespie et al., 2014). A reduction in the overall dysphonia (CSID) is also hypothesized due to the perceived reduction of the overall dysphonia severity that has been reported for connected speech in PD following LSVT (Baumgartener et al., 2001).

Method

Participant information is listed in Table 7. Nine adults were included in this study (six males and three females). Ages ranged between 52 and 81 years (mean = 65, SD = 11.20). Each participant's medical diagnosis was idiopathic PD, and the severity of hypokinetic dysarthria was assessed using the Mayo Clinic Rating Scales (Duffy, 2005). Participants were evaluated by an experienced ASHA certified speech language pathologist (SLP) to verify the presence of hypokinetic dysarthria with hypophonia before their enrollment in the project. A consent form approved by the Institutional Review Board of the University of Memphis was signed by each participant. Prior to enrollment in the study, laryngeal endoscopic examinations were completed by an otolaryngologist for all participants to rule out any VF pathologies that may contraindicate enrollment in a high-effort voice treatment. The enrolled participants agreed to continue following their regular anti-Parkinson medication schedules as prescribed by their physician throughout the study period. No additional speech or voice treatment besides LSVT was provided and no participants had received LSVT prior to the study.

Table 7

*Clinical Characteristics of Ten Speakers with Idiopathic Parkinson's Disease**

Participant	Sex	age	Years since diagnosis	medication	Single word Intelligibility Score**	Mayo Clinic Dysarthria Rating Scales
1	M	67	7	A, C	62%	Marked monopitch, monoloudnes, reduced loudness, audible inspiration, short phrases, increased rate, breathy voice (continuous), imprecise consonants; moderate reduced stress; mild alternating loudness and harsh voice
2	F	62	11	B	56%	Severe strained-strangled voice, voice tremor, voice stoppages, prolonged intervals; marked pitch breaks, monopitch, voice tremor, monoloudness, reduced loudness, harsh voice, reduced rate, reduced stress, imprecise consonants; moderate breathy voice (transient) and weak pressure consonants
3	M	77	6	B	40%	Severe monopitch, monoloudness, reduced loudness, breathy voice, increased rate, reduced stress, short rushes of speech, imprecise consonants, repeated phonemes, irregular articulatory breakdowns; marked harsh voice and palilalia
4	F	61	3	B	60%	Marked monopitch, monoloudness, reduced loudness, voice stoppages, increased rate (segments), Variable rate, short rushes of speech, prolonged phonemes, irregular articulatory breakdowns; Moderate breathy voice (transient), prolonged intervals, inappropriate silence, imprecise consonants

*:A=L-dopa, B = sinemet, C = requip, D = carbo/levodopa, E = amantadine, F = Mirapex, G = comtan, H = sinemet
**as measured by the *Assessment of Intelligibility for Dysarthric Speech*

Table 2 (continued)

Participant	Sex	age	Years since diagnosis	medication	Single word Intelligibility Score**	Mayo Clinic Dysarthria Rating Scales
5	F	81	23	D, E, F	50%	Severe monopitch, monoloudness, harsh voice, strained-strangled voice; marked reduced pitch Level, pitch breaks, increased rate, variable rate, imprecise consonants; moderate weak pressure consonants, repeated phonemes, distorted vowels
6	M	71	27	B, E	NA	Marked monopitch, monoloudness, reduced loudness, breathy voice (continuous), short phrases, inappropriate silences; moderated harsh voice; mild excess loudness variation, reduced stress, prolonged intervals
8	M	52	3	F	62%	Marked monopitch and monoloudness; moderate reduced loudness, breathy voice (continuous), reduced stress; mild harsh voice, reduced rate, simple vocal tics
9	M	46	2	None	55%	Severe monoloudness; marked monopitch, moderate breathy voice (continuous), short phrases, reduced stress, inappropriate silence; mild harsh voice
10	M	68	20	B	29%	Severe short phrases; marked monopitch, monoloudness, reduced loudness, breathy voice (transient), weak pressure consonants, reduced stress, short rushes of speech; moderate alternating loudness, variable rate, inappropriate silences, imprecise consonants, repeated phonemes, irregular articulatory breakdowns; mild prolonged phonemes

*:A=L-dopa, B = sinemet, C = requip, D = carbo/levodopa, E = amantadine, F = Mirapex, G = comtan, H = sinemet
**as measured by the *Assessment of Intelligibility for Dysarthric Speech*

Other than having the same diagnosis and no prior speech or voice treatments, the sample of speakers with PD recruited for this study was clinically diverse. Variable characteristics of the sample included the following: one participant experienced bilateral deep brain stimulation (speaker 6), one participant had a history of bilateral pallidotomy (speaker 5), three participants used hearing aids (speakers 4, 5, and 8), one participant did not take anti-Parkinson medication (speaker 9), four participants were ambulatory (speakers 1, 2, 3, and 8), two participants used walkers for assistance (speakers 4 and 5), and one participant used a wheelchair (speaker 6). Participant histories had a wide range of years since diagnosis. In addition they had great variability of severity of PD and of dysarthria. Single word intelligibility varied from 29% to 62% as measured by the Assessment of Intelligibility of Dysarthric Speech (Yorkston & Beukelman, 1984).

Each participant underwent standard LSVT administered by an ASHA certified SLP who was also a certified LSVT provider. All speakers enrolled in LSVT participated in a total of 16 sessions for four days a week for four weeks. Speech recordings were obtained on three different days within one week before and one week after LSVT. Each speaker was instructed to produce three repetitions of a sustained vowel /ɑ/ holding out the vowel as steady and as long as she or he can and to read the first paragraph of the Rainbow Passage (Fairbanks, 1960). There were no cues for the participant to produce loud production during the pre- and post-treatment assessments. Recordings were collected in a sound booth using a head mounted condenser microphone (AKG C420) with a flat frequency response below 10 kHz, positioned out of the breath stream and 4 cm from the corner of the speaker's lips (Titze & Winholtz, 1993). Signals were digitized directly to disc at a sampling rate of 44.1 kHz using Kay Elemetrics CSL 4300B hardware (KayElemetrics). Acoustic analyses were obtained using the KayPENTAX Analysis of Dysphonia in Speech and Voice (ADSV) software (KeyElemetrics). Prior to ADSV, to approximate the 25 kHz standard for ADSV analysis and the CSID standard (Awan et al., 2010), signals were down-sampled to 22.05 kHz for sustained phonation and for connected speech. For the sustained vowels, each vowel signal was excerpted from a longer file by trimming the onset of the vowel, as well as the offset of the vowel. For connected speech, each connected speech signal was excerpted from the first paragraph of the Rainbow Passage with only the second and third sentences of the passage being analyzed in accordance with ADSV protocol. Both sustained phonation and connected speech file onset were trimmed to assure a 50 ms silent period before and after each production. Because extraneous noise could impact the results, trimming was also performed as needed to remove unwanted sections from an otherwise satisfactory capture such as silence, coughs, throat clears, et cetera.

Changes in connected speech intensity were calculated with reference to recorded calibration tones of known sound pressure level using the 20-log formula, which was obtained by measuring the integer voltage (root mean square (RMS)) of the calibration tone from the recording. Then we measured the RMS quantities from the connected speech sample and placed the obtained values on a dB SPL scale relative to the calibration tone (20*Log(RMS_{voice}/RMS_{Cal}) while adding the dB value observed on the SPL meter during the calibration tone to the given log equation (Buder & Cannito, 2009).

Measures of interest were extracted from the PENTAX Analysis of Dysphonia in Speech and Voice (ADSV) program which included Cepstral Peak Prominence (CPP), CPP Standard Deviation (CPP-SD), the Low/High Spectral Ratio (L/H SR) measure with the default 4 kHz cutoff, and Cepstral/Spectral Index of Dysphonia (CSID). Moreover, to account for the different L/H SR cutoffs (adjusted L/H SR) that have been used for sustained phonation, which was based on Cannito et al., (2006) and Dromey (2003) findings, the cutoff was adjusted to 2 kHz for males and 2.5 kHz for females. This was to provide greater focus on the F1 and F2 regions of the spectrum on sustained phonation (Alharbi et al., in review).

In connected speech, the ADSV default cutoff 4 kHz was used for both connected speech and sustained phonation to be consistent in assessing individual differences. The CSID value for the Rainbow Passage was computed manually using the regression formula reported in Awan et al. (2009), which includes CPP, L/H RS, and L/H RS SD. For both connected speech and sustained phonation, participants were recorded on three consecutive days preceding and three consecutive days following LSVT with three trials performed for the sustained vowel /ɑ/ per day.

Both intra- and inter-observer measurement reliability were calculated for 67% of sound files for sustained vowels and 51% of sound files for connected speech per participant productions by trained graduate students in a speech-language pathology program. For reliability assessments, all vowel signals and connected speech were again segmented from the longer recordings and re-trimmed to include the silent period, then submitted to the ADSV for analysis. For intra-analyst reliability, data were not reanalyzed until a 4-month waiting period had passed. Reliability was high for all selected ADSV measures of sustained vowels and connected speech for both inter-analyst ($r > 0.90$, $p < 0.001$) and intra-analyst ($r > 0.90$, $p < 0.001$) comparisons. Overall vocal SPL (dB) was analyzed using paired sample *t*-tests averaged across days within each pre-T_x period and post-T_x period.

The present study included four stages of analysis. First, it was necessary to evaluate the effect of LSVT in terms of its primary target variable, acoustic voice intensity (dB_{spl}), on the connected speech production of current sample of speakers with PD. This was accomplished by comparing their dB levels of their recorded rainbow passages to test the a priori prediction that dB would increase significantly from pre-to-post treatment based on extensive prior literature which supports this claim. A paired-samples t-test was conducted at alpha level = .05 (two-tailed) was computed at alpha level = .05 (one-tailed). Confirmation of this prediction was required to motivate further evaluation of the experimental hypothesis with respect to spectral/cepstral measures.

The second stage of analysis was to examine the experimental hypotheses regarding the effect of LSVT on selected spectral/cepstral measures of voice in connected speech. A two-way repeated measures ANOVA was used to examine changes in spectral/cepstral measures for connected speech from pre-to-post LSVT. Within-participants variables were Treatment Period (Pre-T_x, Post-T_x) and Recordings Days (days 1, 2, and 3 Pre-T_x and days 1, 2, and 3 Post-T_x). An overall α-level = 0.05 was Bonferonni adjusted to 0.0125 for testing the significance of effects for each of the four acoustic variables. In addition, a Bonferroni correction procedure was used to counteract the problem of multiple comparisons (Holm, 1979).

The third stage of analysis was to descriptively compare changes in connected speech with changes in sustained vowels reported in the first study (Alharbi et al., in review). This was conducted by simply comparing which spectral/cepstral variables were statistically significant and also by inspecting the means and SDs for both studies, the sustained phonation and the connected speech. The fourth stage of analysis was to examine individual differences in both sustained phonation and connected speech in response to LSVT. A change criterion of one half standard devistion (SD) of the post treatment distribiution was employed. The value was based on the criteria for identifying a meaningful change using the Cohen's d statistic (Cohen, 1988). This criterion is generaly regarded as a moderate effect size, and therefore was used to detrmine a meaningful increase/decrease in individual participant's vocal function from pre- to post-treatment. The SD was considered based on the post treatment distribution for each acoustic variable. Each participant's improvement was calculated relative to the differences between the pre and post treatment values for both sustained vowel and connected speech. For each participant the four acoustic variables were averaged pre-treatment and post-treatment across days for connected speech and across days and trials for sustained phonation separately.

Results

In the current study, the first stage of analysis was to examine intensity changes to provide a validation for the treatment efficacy. Results indicate that before LSVT, the speakers' mean intensity across days of connected speech was 78.8 dB_{spl}. Following treatment, the mean connected speech intensity was 81.7 dB_{spl}. These results indicated a statistically significant increase in intensity (dB_{spl}) for the connected speech task from pre-to-post treatment (t (8) = -2.32 $p < 0.049$), which is in keeping with expectations of the treatment program.

The second stage of analysis, was the primary goal for the current study, which was to examine the effect of LSVT on selected spectral/cepstral measures of voice in connected speech for participants with PD. Table 8 provides the means and SDs for each measure obtained from the PD participants' connected speech before and after LSVT, averaged across recording days. A statistically significant difference from pre-to-post LSVT was found for one acoustic variable: CPP (F (1, 8) = 10.51, $p = 0.012$, $\eta^2 = .57$). The other acoustic variables did not differ significantly from pre-to-post treatment CPP-SD (F(1, 8) = 4.67, $p = 0.063$, $\eta^2 = 0.37$), L/H SR 4kHz cutoff (F(1, 8) = .64, $p = 0.445$, $\eta^2 = 0.08$), , and CSID (F(1, 8) = 9.56, $p = 0.015$, $\eta^2 = 0.55$). There were no statistically significant main effects or interactions for days. Sample analyses are presented in Figure 3. It should be noted that CSID, while not strictly significant at the family-wise adjusted alpha level, was very close to this cutoff and exhibited a strong effect size. Thus, the Holm-Bonferroni correction procedure CSID was applied to counteract the problem of loss of power in multiple comparisons. After applying the Holm-Bonferroni correction procedure CSID exhibited a statistically significant effect (p = .015, given Holm-Bonferroni criterion of p = .016 <.016) (Holm, 1987).

Table 8

Descriptive statistics summary for PD group for connected speech before and after treatment

Dependent Variables	Pre-LSVT	Post-LSVT
	Mean (SD)	Mean (SD)
CPP	5.96 (1.23)	6.67 (1.25)
CPP SD	3.34 (.49)	3.63 (.71)
L/H SR 4 kHz	35.30 (4.06)	36.12 (5.24)
L/H SD	10.98 (1.88)	10.74 (1.62)
CSID	13.83 (16.59)	6.47 (15.66)

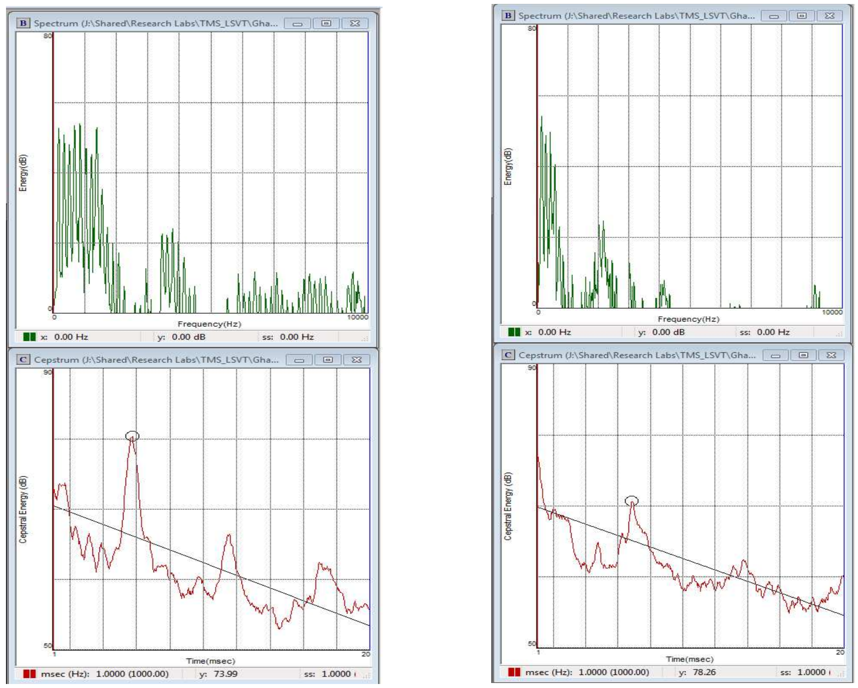

Figure 3. Rainbow Passage production of PD partisipent # 5 demonstrating increased harmonic structure and reduced spectral noise pre- to post-treatment (Top panels). Bottom panels demonstrate increased CPP from pre- to post-treatment. Pre-treatment CPP = 5.34 and CSID = 26.41. Post-treatment CPP = 7.46 and CSID = 1.01.

The third stage of analysis was to investigate task-related differences for speakers with PD as a whole for both connected speech and sustained phonation. Table 9 provides the means and SDs for each measure obtained from the PD participants' sustained vowel tasks before and after LSVT, averaged across recording days and trials (Alharbi et al., in review). The sustained vowel data is being provided in order to compare post-treatment change across the two speech elicitation tasks. In connected speech, CPP and CSID were statistically significant, while in sustained phonation four acoustic variables were statistically significant including CPP, CPP-SD, Adjusted L/H SR, and CSID.

Table 9

Descriptive statistics summary for PD group sustained phonation before and after treatment

Dependent Variables	Pre-LSVT	Post-LSVT
	Mean (SD)	Mean (SD)
CPP	9.96 (1.72)	12.35 (1.38)
CPP SD	1.60 (.49)	1.25 (.33)
L/H SR 4 kHz	36.47 (5.50)	34.60 (5.60)
Adjusted L/H SR	34.43 (6.12)	28.94 (5.05)
L/H SD	2.67 (.53)	2.45 (.46)
CSID	35.84 (13.80)	21.87 (10.18)

Adjusted is 2 kHz cutoff for males and 2.5 kHz cutoff for females

The fourth stage of analysis was to examine individual differences in response to LSVT across the experimental measures. Table 10 summarizes the results for all participants, indicating who met and who did not meet the criterion (.5 SD) for the selected ADSV measures for both connected speech and sustained phonation. Intensity improvement following LSVT on sustained vowels was demonstrated by seven speakers while on connected speech intensity improvement following LSVT was demonstrated by six speakers (See Figure 4). CPP attained the half standard deviation criterion for seven participants in sustained phonation while for connected speech five participants attained the criterion (see Figure 5). Four participants showed an improved CPP in both sustained phonation and connected speech. One participant showed an improved CPP in connected speech and no improvement of CPP in sustained phonation. All participants with PD demonstrated a reduction in their CPP variability (CPP-SD), while four speakers demonstrated an increased

CPP-SD following LSVT in connected speech (See Figure 6). In the measure of L/H SR in sustained phonation, five speakers showed a reduction in the L/H SR. For connected speech, three speakers demonstrated an increase in L/H SR following treatment, which suggests an increase in the low frequency energy following treatment (See figure 7). An overall reduction of dysphonia severity on sustained phonation was observed in eight speakers, while in connected speech an overall dysphonia severity reduction was demonstrated in four speakers (See Figure 8).

Table 10

Individual differences in response to treatment for ADSV selected measures for both sustained phonation and connected speech

Participant	Task	Sustained Phonation					Connected speech				
	Measure	dB SPL	CPP	CPP-SD	L/H SR	CSID	dB SPL	CPP	CPP-SD	L/H SR	CSID
Post-TX .5 SD		> 2.89	> .62	< .11	<.62	< 4.11	> 2.45	> .62	> .38	>2.61	< 4.11
4		*	*	*	*	*	*	*	*		*
5		*	*	*	*	*	*	*	*		*
6		*	*	*		*	*	*	*	*	*
1		*	*	*	*	*		*	*		*
8		*	*	*	*	*	*				
9		*		*		*	*			*	
3		*	*	*		*	*				
2			*	*						*	
10				*	*			*			

Note. An asterisk indicates a participant who met the one half SD criterion.

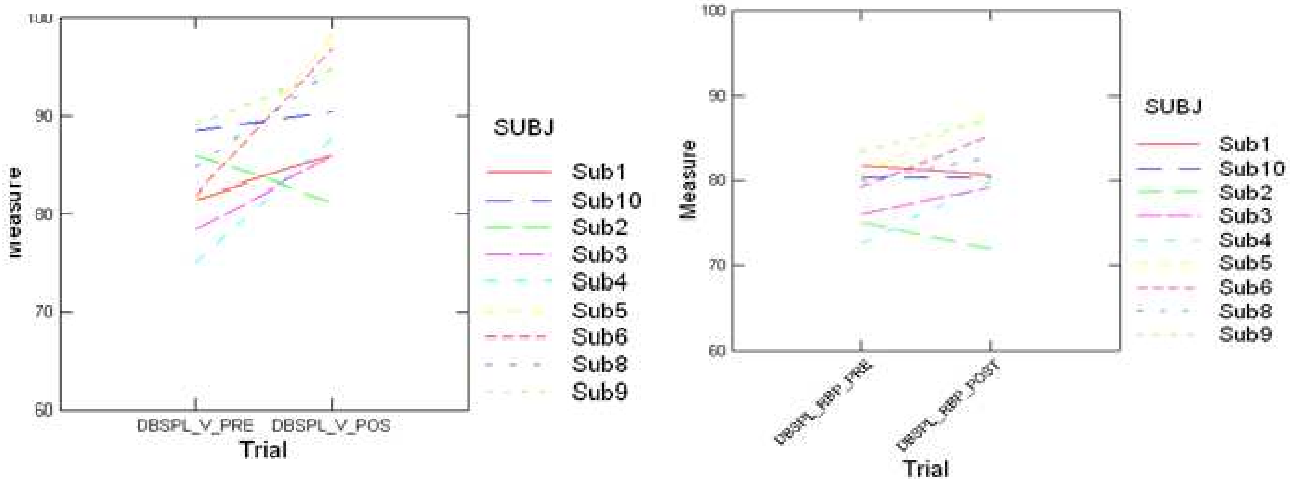

Figure 4. Line graph showing averaged pre-Tx and post-Tx values for vocal intensity changes per participant for both sustained phonation and connected speech.

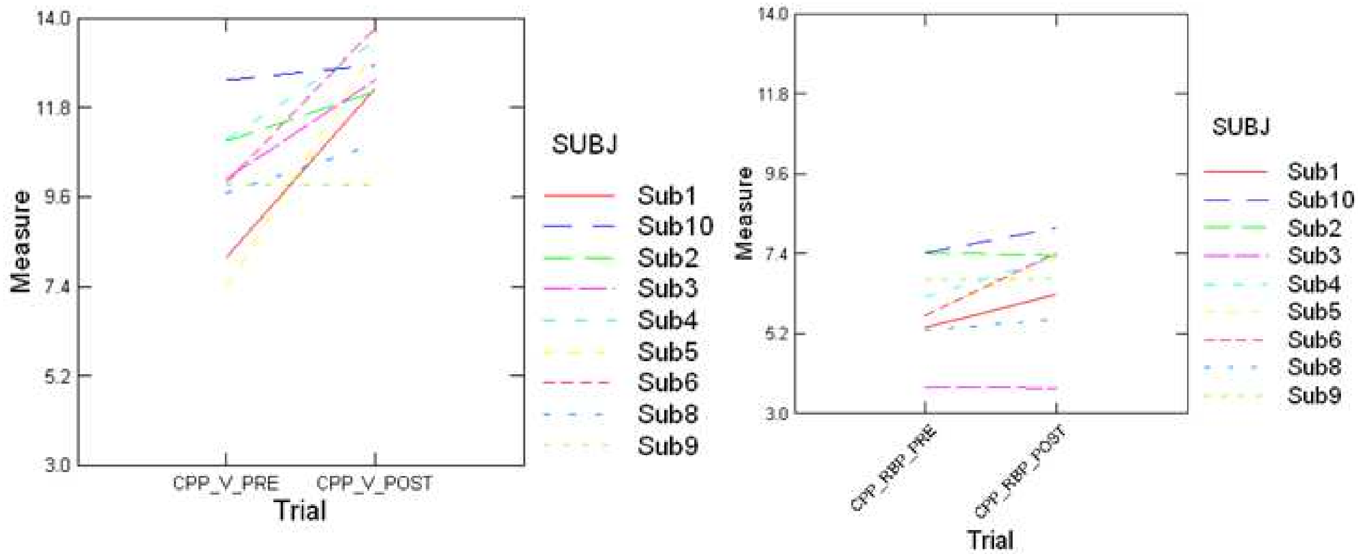

Figure 5. Line graph showing averaged pre-Tx and post-Tx values for CPP per participant for both sustained phonation and connected speech.

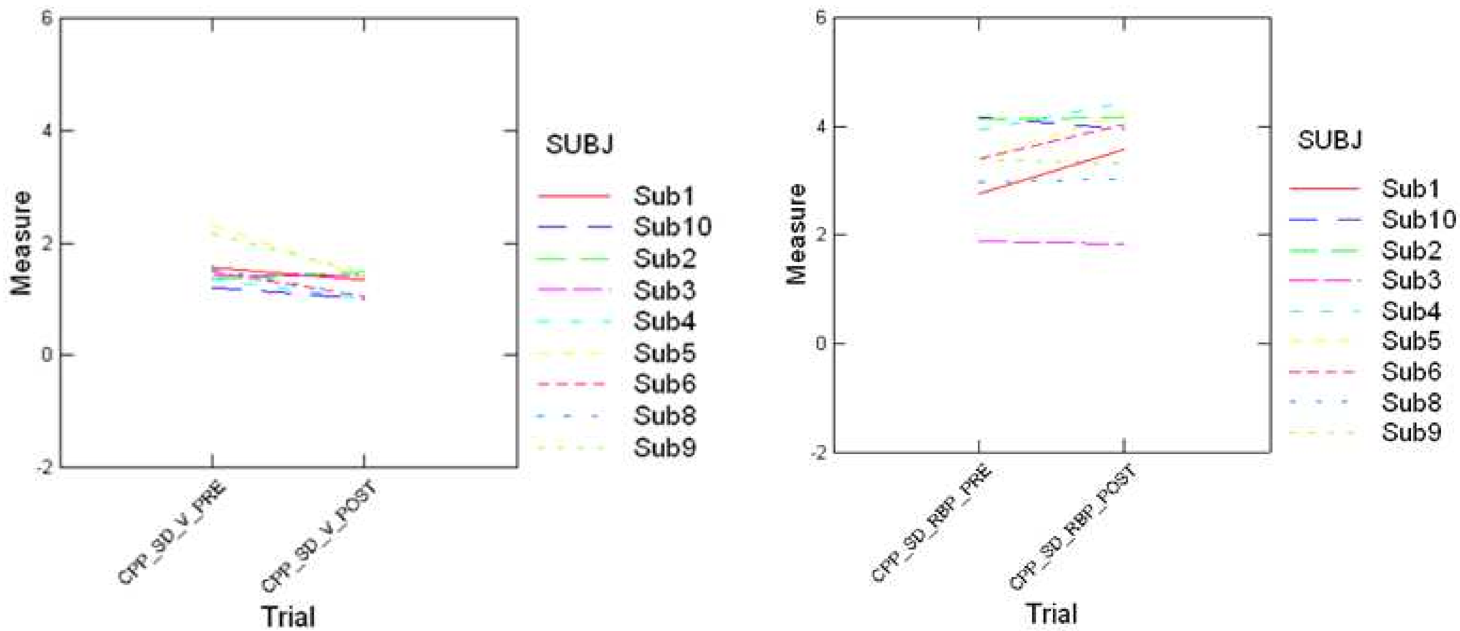

Figure 6. Line graph showing averaged pre-Tx and post-Tx values for CPP-SD per participant for both sustained phonation and connected speech.

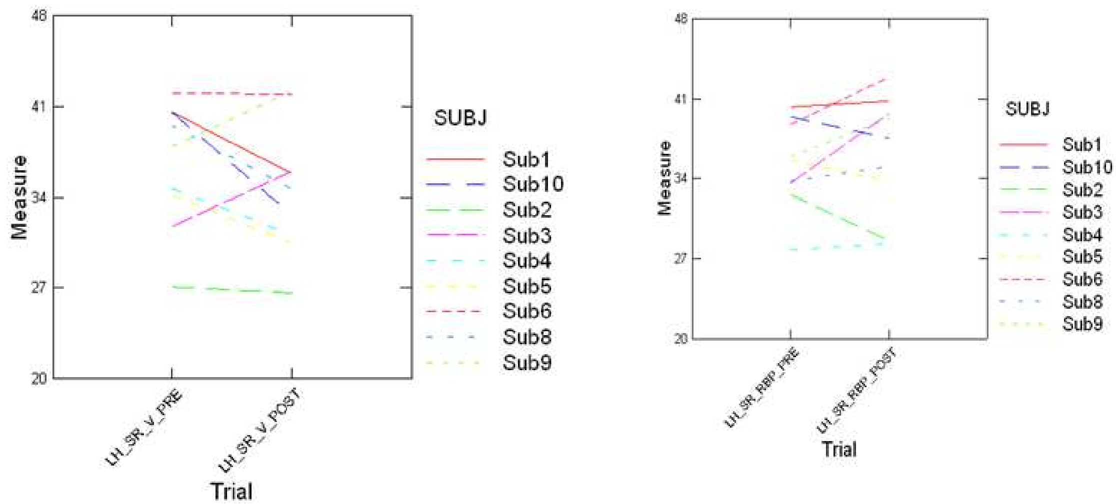

Figure 7. Line graph showing averaged pre-Tx and post-Tx values for L/H SR per participant for both sustained phonation and connected speech.

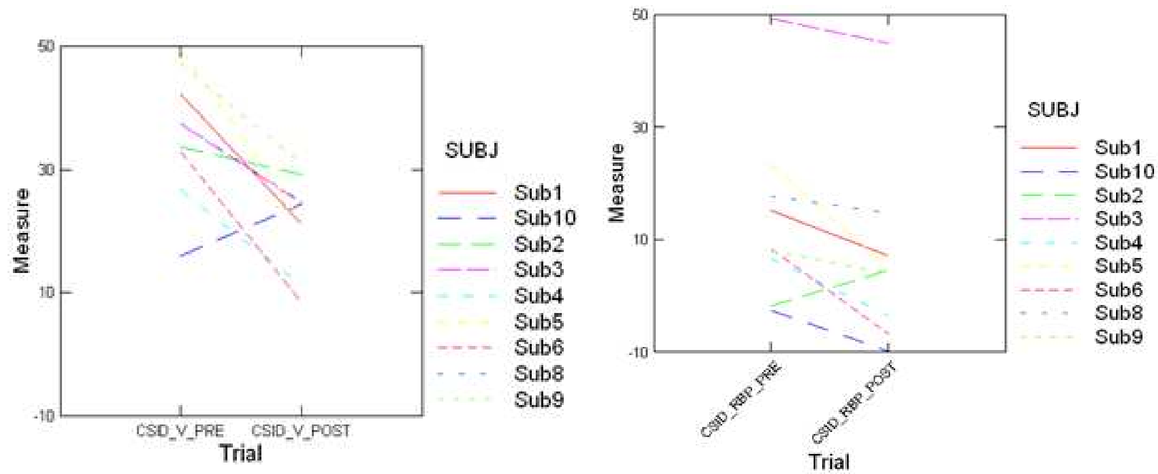

Figure 8. Line graph showing averaged pre-Tx and post-Tx values for CSID per participant for both sustained phonation and connected speech.

Discussion

The primary purpose of this study was to assess hypotheses regarding the effect of LSVT on selected spectral/cepstral measures of voice in connected speech. Secondary spectral/cepstral analyses were used to descriptively compare changes in connected speech with changes in sustained vowels reported in the sustained phonation study reviewed in chapter 2. In addition, a second secondary goal was to examine individual differences in response to LSVT across the experimental measures. The current study will first discuss the primary goal and then the secondary goals.

Effect of LSVT on spectral/cepstral measures in Connected Speech

The spectral/cepstral analysis demonstrated that out of the four spectral/cepstral variables chosen, CPP and CSID were the only measures that detect treatment-related changes in connected speech. These findings indicated that the participants had better harmonic structure following treatment, which indicated the CPP was sensitive to spectral changes resulting from LSVT and was the voice quality variable that changed the most in response to LSVT for connected speech. Even with the inclusion of the laryngeal and supralaryngeal articulation and prosodic variations in connected speech, the CPP was shown to be the most sensitive cepstral measure to LSVT in that it was not influenced by speaking condition, which was in agreement with Watts & Awan (2011).

These spectral changes are consistent with, and indirectly support, the findings of previous studies demonstrating increased glottal closure following intensive voice therapy (Smith et al., 1995), increased subglottal pressure, and decreased EGG open quotient post LSVT (Dromey et al., 1995; Ramig & Dromey, 1996). In part, the present findings may also reflect the sensitivity of CPP to variations in vocal loudness/intensity (Maryn et al., 2009). CSID was statistically significant, which indicated that CSID was a predictive measure of perceived dysphonia. This finding supports the clinical significance of the present results for a treatment-related voice change post LSVT (Peterson et al., 2013; Alharbi et al., in review). The present acoustic finding of decreased dysphonia is also consistent with previous perceptual findings of improved voice quality after LSVT in connected speech (Baumgartner et al., 2001). Even with the influence of L/H SR (decrease after LSVT) on sustained phonation as reviewed in the second chapter, CSID was an applicable measure to detect treatment effects in this population for both connected speech and sustained phonation due its large effect size.

CPP-SD in the connected speech condition failed to demonstrate any significant changes following treatment. The present findings for connected speech were not consistent with Watts & Awan (2011) who demonstrated that the CPP-SD was an effective measure in examining treatment outcome on hypo-functional groups. The small sample size or the number of dependent variables ($M = 4$) may have affected the ability of the statistics to reveal a significant difference. In addition, it may be related to the great variability in severity.

L/H SR did not show any significant change in response to treatment in connected speech. This finding was not consistent with findings reported by Watts & Awan (2011), who found that L/H SR was able to demonstrate treatment related change in individuals with dysphonia of various etiologies. In addition, the finding was not consistent with Gillespie et al. (2014) who demonstrated that, in speech, the L/H ratio and its SD may be an important outcome measure to track responses to behavioral intervention in single voice disorder, which included vocal fold lesions, primary muscle tension dysphonia, vocal fold atrophy or unilateral vocal fold paralysis before and after treatment. The current findings may not be consistent with Watts & Awan (2011) and Gillespie et al., (2014) because the previous studies did not use participants with PD. The participants in this study may have had different degrees of breathiness or roughness than the participants in the previous studies. Additionally, the lack of significance of the L/H SR on connected speech may be due to the use of an arbitrary default cut off frequency of 4 kHz for computation of the intensity ratio. Previous findings for sustained phonation in speakers with PD in review suggested that restricting the L/H SR cutoff to a region just above the second formant and below the third formant was more sensitive in detecting treatment effect in PD population (Alharbi et al., in review). However, in connected speech, adjusting the L/H SR cutoff was not possible due to the variability of formants across a variety of vowels in connected speech.

Effect of task before and after LSVT on spectral/cepstral measures

CPP and CSID were effective measures in terms of detecting treatment-related change in sustained phonation, which was consistent with both Paterson et al., (2013) and Alharbi et al., (in review). As previously discussed, CPP-SD in sustained phonation was observed to be a statistically significant measure (Alharbi et al., in review) but not in connected speech. The lack of significant change of the CPP-SD in connected speech may be related to the degree of severity prior to treatment. The reason L/H SR in connected speech did not show statistically significant results may be because lowering the cutoff is more sensitive in detecting treatment effect in participants with PD but lowering the cutoff was not possible in connected speech.

Individual differences before and after LSVT on spectral/cepstral measures

CPP findings indicated that in the present sample, not all participants achieved the .5 SD criterion but as a group still had better harmonic structure following treatment as reflected in the CPP findings. The finding that fewer speakers improved on CPP in connected speech than in sustained vowels is not surprising because Watts & Awan (2011), when evaluating the diagnostic value of spectral/cepstral measures to differentiate hypo-functional speakers from healthy speakers, demonstrated a smaller effect of CPP in connected speech when compared to sustained phonation. In addition, when comparing the correlation of CPP with the dysphonia severity rating, a stronger correlation was observed in sustained phonation compared to connected speech (Awan et al., 2010). The present findings agree with Awan & Watts (2011) that even within the same speaker, the degree of dysphonia severity and/or voice quality type may be more evident in sustained vowels than in connected speech.

CPP-SD findings indicated a positive effect of the LSVT in increasing some of the participants' speech variability in connected speech. During sustained phonation, CPP-SD was the only measure which met the criterion for all participants, indicating the harmonic structure was more consistent and steady following treatment. While in connected speech, it did show improvement in some participants this may be related to the degree of variability in severity.

L/H SR findings in some of the participants indicated that in the present sample high frequency energy increased following treatment. For example, participants who did show an improved L/H SR after treatment may have had more imprecise consonants before treatment than participants who did not show improvement as what has been perceptually detected in participant # 2 who was very mild severity prior to treatment. In prior work on disordered voices other than PD, an improved voice showed an increase in the L/H SR (Awan et al., 2010). More studies are needed to understand the direction of change in the L/H SR following treatment in speakers with PD in relation to healthy controls.

CSID findings indicated that only participants who showed a reduction in overall severity in connected speech also demonstrated a reduction in the overall severity of sustained phonation (Participants # 1, 4, 5, 6). Among these participants, participants # 1 and 5 were very breathy prior to treatment in both connected speech and sustained phonation while following treatment their voices were much stronger with no breathiness detected in all days and trials for sustained phonation and all days for connected speech. These participants also improved their CPP, which may explain the reduction of the CSID.

In summary, cepstral/spectral measures have been shown to be valid measures for estimating dysphonia severity in both sustained vowels and continuous speech (Awan et al., 2013; Gaskill et al., 2017) and for differentiating typical and disordered voice production. The present study extends the use of these measures to speakers with PD both for characterizing speech and voice aspects prior to treatment and for quantifying treatment outcomes. The present findings also support the use of LSVT as a treatment approach for improving voice quality in addition to intensity in PD. The current study supports the use of the CPP and CSID as outcome measures for documenting phonatory changes in connected speech following LSVT. In addition, it supports the use of the CPP, CPP-SD, Adjusted L/H SR, and CSID as outcome measures for documenting phonatory changes in sustained phonation following LSVT. Investigating individual differences demonstrated that participants # 1, 4, 5, and 6 did improve on CPP, CPP-SD and CSID in both tasks, with more participants demonstrating an improvement in sustained phonation than in connected speech. In general, spectral/cepstral measures were representing the degree of severity in voice quality in some of the participants. For example, a few participants did not show a vocal intensity improvement but did show slight spectral/cepstral measures improvement. The participants that exhibited this pattern were very mild breathy prior to treatment, as with participant #2. In addition, participants who did show improvements were those who had a breathy voice quality prior to treatment while following treatment there were no breathiness detected as seen in participants #s 1 & 5. Present results agree with those obtained by Gillespie al. (2014) indicating that voice change is not consistently demonstrated by CPP, CPP-SD, L/H SR, L/H SR SD, and CSID for all disorders. In addition, the present findings suggest that not all individuals will exhibit within-participants effects or the effects may be very small, and these may vary with different elicitation tasks.

Further studies are needed to replicate these findings with a larger data set. In addition, studies are needed to determine the reason for the inconsistency of the spectral/cepstral measures findings across speaker. Furthermore, it is important to extend ADSV analyses to phonation elicited at long-term follow-up post LSVT. It will also be of interest to directly compare present spectral/cepstral measures with other harmonic spectral analytic techniques in both sustained vowels and connected speech produced by individuals with PD. In addition, it will be important to perceptually evaluate voice quality in the present participants to determine how their cepstral/spectral measures may correlate with perceptual scaling judgements made by trained clinicians. Furthermore, it is important to compare the spectral/cepstral measures findings with other acoustics measures such as electroglottographic (EGG) measures and video-laryngoscopy to document the detected improvement following LSVT.

Chapter 4: General Conclusion

The two studies included in this dissertation investigated voice quality in participants with Parkinson's Disease (PD) in two ways: The first study investigated the effect of LSVT on selected cepstral/spectral measures of sustained /ɑ/ vowels. The second study served to assess the effect of LSVT on selected spectral/cepstral measures of voice in connected speech. A secondary goal was to descriptively compare changes in connected speech with changes in sustained vowels. In addition, it was of interest to examine individual differences in response to LSVT across the experimental measures in connected speech and compare findings with what was observed in sustained phonation (Alharbi et al., in review).

The first study (Chapter 2) demonstrated that Cepstral Peak Prominence (CPP), CPP standard deviation (SD), and Cepstral Spectral Index of Dysphonia (CSID) improved significantly following LSVT, with similarly strong effect sizes for both CPP and CSID. Cepstral/spectral measures have been shown to be valid measures for estimating general dysphonia severity in both sustained vowels and continuous speech (Awan et al., 2013; Gaskill et al., 2017) and for differentiating typical and disordered voice productions. The first of the two studies reported here extends these findings to support the use of CPP, CPP-SD, and CSID as treatment outcome measures for documenting phonatory changes before and after LSVT in PD. Low/High Spectral Ratio (L/H SR) did not significantly differ using the default cutoff 4 kHz in sustained phonation. However, based on prior work by Cannito et al., (2006) on spectral measures of voice quality in PD, findings suggested the utility of lowering the L/H SR cutoff to 2 kHz for males and 2.5 kHz for females.

The findings of the primary goal of the second study support the use of both CPP and CSID in connected speech. It should be recalled that the CSID is a composite measure based on a regression formula. CSID was comprised of some of the spectral measures that did not exhibit statistically significant change (i.e., L/H ratio and L/H ratio SD). CSID nonetheless reflected the positive effect of treatment on voice quality, which indicated that the CPP may have been the largest contributor on the CSID.

Task comparisons indicated that CPP and CSID were the best predictors for voice quality for both connected speech and sustained phonation, with similarly large effect sizes for both sustained phonation and connected speech. The lack of significance of the L/H SR may be related to the fact that L/H SR has a different direction for individuals with PD: voice improvements in the PD population exhibited an increase in high frequency energy, while in other dysphonic populations this measure would indicate a breathy voice.

Individual differences revealed that only four participants showed an improvement in sustained phonation and connected speech on CPP, CPP-SD, and CSID, while the other participants demonstrated greater improvements in sustained phonation than in connected speech. Even though not all the participants achieved the .5 SD Post-TX criterion for improvement, CPP by itself was a strong and robust sensitive acoustic variable of voice quality for both sustained phonation and connected speech on both tasks and in most of the participants. In addition, CPP-SD was the only measure that achieved the .5 SD criterion for all the present participants in sustained phonation. The greater and more universal improvements on sustained phonation do not mean that sustained phonation is a better task than connected speech for detecting treatment-related changes. Rather, it may mean that the degree of severity of a participant's dysarthria may affect connected speech more than sustained phonation. Another reason may be the fact that the direction of the L/H SR affected the outcome in connected speech.

Limitations for both studies are the small sample size, no healthy controls. Also both studies lack perceptual evaluations of changes from pre to post-therapy, which may be an important step for better understanding the lack of significance for both tasks in selected measures either at the group level or individually. Future studies can address this limitation by having a larger sample size.

Findings from both studies lead us to several considerations for evaluating speakers with PD. First, lowering the L/H SR in sustained phonation was more sensitive than the ADSV default cutoff in detecting treatment effects in a population with PD. Second, a clinician should perceptually judge participants for their candidacy for both LSVT and ADSV because LSVT is for truly hypofunctional voice quality and cepstral analysis is not highly effective in characterizing severely hyperfunctional, strained voices (Awan, Roy, Zhang, & Cohen, 2016). This consideration was raised by the need to exclude participant 7 who exhibited a severely reduced pitch level, demonstrating that a diagnosis of hypokinetic dysarthria with hypophonia may not be sufficient for ruling out candidates who exhibit a hyperfunctional voice quality. These findings confirm prior general dysphonia studies (Gillespie et al., 2014; Watts & Awan, 2011) indicating that ADSV is an effective voice assessment tool. In addition, both studies in connected speech and sustained phonation inform the researcher that ADSV is sensitive to voice quality type, dysphonia severity, and tasks.

In addition, both studies highlight points that need further investigation. First, the presence of subharmonics in the voice signal increase the energy and this may interact with treatment and may make pretreatment look better or worse. Therefore, before confirming that the cepstrum is describing the treatment effects, researchers may better investigate if cepstrum is appropriate when measuring the main harmonic rather than the subharmonic. Due to this, researchers need to investigate why the CPP algorithm breaks down during the presence of subharmonics in the voice signal, which may affect the cepstral analysis. Even though the cepstrum, in comparison to many other quality measures such as jitter and shimmer, does not require cycle-to-cycle periodicity detection from the waveform and does not rely on F_o extraction, CPP determination does require F_o when choosing the main rahmonic.

A second topic for future investigation may be to develop a CSID formula suited for a person with PD that incorporates the new L/H SR direction. Third, researchers must perceptually evaluate the degree of severity for speakers with PD to account for variability that also may help to explain the lack of significance on the spectral/cepstral measures. A fourth area of future research would compare these measures with electroglottographic (EGG) measures and video-laryngoscopy to document the detected improvement in the first and second studies. Fifth, future research should apply spectral/cepstral analysis in different nationalities with PD because ADSV may also be sensitive to language differences, especially in connected speech.

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