The Ability of Persons with Parkinson's Disease to Manipulate Vocal Intensity and Articulatory Precision in an Intra-Operative Setting

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B.A., Communication Science & Disorders, University of Pittsburgh, 2018

Submitted to the Graduate Faculty of

School of Health and Rehabilitation Sciences

of the requirements for the degree of

Master of Science

University of Pittsburgh

2020

UNIVERSITY OF PITTSBURGH

SCHOOL OF HEALTH AND REHABILITATION SCIENCES

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March 20, 2020

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Parkinson's disease is a degenerative neurological disease associated with decreased basal ganglia control circuit output, leading to decreased facilitation of cortical motor areas and subsequent motor impairments (Wichmann & DeLong, 1996). Motor impairments, including rigidity, bradykinesia, reduced range of motion and difficulty initiating movement, impact both respiratory function and speech in persons with Parkinson's disease (PWPD), often leading to hypophonia and hypokinetic dysarthria (Darling & Huber, 2011). Hypokinetic dysarthria includes, among other characteristics, reduced loudness and imprecise articulation, and therefore reduced speech clarity.

The purpose of this study was to determine if PWPD were able to manipulate speech intensity and articulatory precision in soft versus loud stimulus presentation conditions in an intra-operative environment. Articulatory precision was measured using the F2 ratio, based on the second formant values of the vowels /i/ and /u/ (Sapir, 2007). As /i/ is produced anteriorly in the oral cavity and /u/ is produced posteriorly, an increase in this ratio is anticipated to accompany greater articulatory precision. It was hypothesized that PWPD would be able to increase vocal intensity, which would result in larger F2 ratios.

Participants consisted of 16 PWPD undergoing surgery for deep brain stimulation and simultaneous recording in the subthalamic nucleus and cortex. Participants repeated CVCVCV

utterances presented auditorily at soft and loud levels. Acoustic signals were recorded and average vowel intensities and second formant values for /i/ and /u/ productions within each utterance were extracted. Second formant values were then used to calculate the F2 ratio for each utterance.

Wilcoxon Signed-Rank Tests revealed that, while intensity significantly increased in the loud compared to the soft condition, the F2 ratio did not demonstrate this increase. Of particular interest, examination of individual participants revealed that 3 patients did not increase intensity in the loud stimulus condition. When only participants who increased intensity were included in subsequent analyses, the F2 ratio did demonstrate a significant increase in the loud stimulus condition.

The current study demonstrates that, even with methodological differences as a result of the intra-operative environment, when patients are able to increase speech intensity, they also increase articulatory precision.

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Preface

Many people deserve much credit and many thanks for the creation of this thesis. Thank you to Dr. Alan Bush, Dr. Anna Chrabaszcz, Christina Dastolfo-Hromack, Dr. Julie Fiez, Dr. Lori Holt, Dr. Witold Lipski, Dr. Fernando Llanos¸ Tara Pirnia, Dr. Mark Richardson and Dr. Susan Shaiman, for the formulation of the research questions and grant purpose, their assistance in accessing, processing and analyzing the data, and for letting me work on their project with them. Additional thanks goes to Dr. Bharath Chandrasekaran and Dr. Sheila Praat for their help and service on my committee. Thank you to Anthony Sicilia for the technological support (the correlations would not exist without you). Thank you to my friend, Katie McGovern, for completing a thesis alongside me and serving as both a teammate and emotional support (especially the emotional support). Finally, thank you to Dr. Susan Shaiman for her support, patience, instruction and guidance as my thesis advisor. You have taught me and guided me so much throughout the past two years, and I cannot thank you enough!

1.0 Introduction

Parkinson's Disease (PD) is a degenerative neurological disease (Darling & Huber, 2011). This disease typically is associated with decreased basal ganglia control circuit output, which leads to decreased facilitation of cortical motor areas and subsequent motor impairments (Wichmann & DeLong, 1996; Duffy, 2013). Such motor impairments include rigidity, bradykinesia, reduced range of motion, and difficulty initiating movement (Darling & Huber, 2011). These motor impairments serve to impact both respiratory function and speech in persons with PD (PWPD), often leading to hypophonia and hypokinetic dysarthria (Darling & Huber, 2011). Typical characteristics of hypokinetic dysarthria include monopitch, monoloudness, reduced loudness, inappropriate silence, variable rate, short rushes of speech, and syllable repetitions (Darling & Huber, 2011). Additionally, due to reduced range of motion, such individuals also exhibit imprecise articulation, and therefore reduced speech clarity. Recent evidence has suggested that both instructing and training PWPD to speak with greater vocal intensity results in greater displacement of articulatory movements, and therefore more precise and distinctive articulation (Sapir et al., 2010; Sapir et al., 2007; Tasko & McClean, 2004; Spielman et al., 2011). The purpose of this study is to examine PWPD's ability to increase vocal intensity and articulatory precision during repetition of auditorily-presented 3-syllable CV syllables at both soft and loud intensity levels. Articulatory precision will be measured using the F2 ratio (Sapir et al., 2007; Sapir et al., 2010), an acoustic measure of vowel formant frequencies that is related to displacement of the articulators (Sapir et al., 2010).

This paper will begin by examining how both healthy normal speakers and PWPD alter their speech intensity levels. This will be accomplished by reviewing relevant literature examining various methods used to elicit increases in vocal loudness, as well as the respiratory and laryngeal musculature necessary to do so. Following this, the literature examining articulatory function and precision in both healthy normal controls and PWPD will be reviewed. Articulatory precision can be indirectly measured utilizing measures of acoustics, specifically measures examining formant frequencies which comprise different vowels. Finally, the relevant literature regarding whether such increases in vocal intensity produce increases in articulatory precision in both PWPD and healthy normal controls will be examined.

1.1 Loudness Production Background

Intensity is defined by Zemlin (1997) as, “the rate of energy flow per unit of area of surface” (p.422). The greater energy in a sound wave, the greater the intensity, and the less energy in a sound wave, the lower the intensity. This measure is objective, and is made by measuring sound pressure level (SPL) in decibels (dB). Loudness, on the other hand, is subjective, and is defined by Uppenkamp and Rohl (2014) as, “the perceptual correlate of intensity” (p.65). In other words, the greater the intensity, the louder an individual will perceive that sound, and the lower the intensity, the softer an individual will perceive the sound. However, loudness cannot be measured objectively, as its perception is entirely dependent upon the individual’s hearing thresholds; an individual with hearing loss may deem a sound of a high intensity soft, while an individual of hearing within normal limits (WNL) may deem the sound loud. Throughout the literature examined within this paper, intensity and loudness frequently are used interchangeably, and as a result, they have been so throughout this paper.

Increasing loudness requires adjustments in both the respiratory and laryngeal systems (Baker et al., 2001). Increasing vocal intensity requires a greater amount of air to be inhaled and exhaled during speech production. Inhalation is achieved by greater expansion of the lungs via increased contraction of inspiratory musculature, e.g. the diaphragm, external intercostals, pectoralis major/minor (Zemlin, 1997). Contraction of inspiratory musculature expands the ribcage, and also expands the lungs, which are attached to the ribcage via the pleural linkage (Zemlin, 1997). The greater the lungs are expanded by contraction of these muscles, the larger the amount of air able to be held within the lungs (Zemlin, 1997).

As described by Zemlin (1997), the production of loud phonation requires increased exhalatory drive from the lung-thoracic unit, which consists of the lungs, the ribcage to which the lungs are connected, and the diaphragm. Another necessary component includes increased medial compression and tension of the vocal folds. Increased medial compression and tension are accomplished by contraction of select intrinsic laryngeal muscles, including cricothyroid, thyroarytenoids, interarytenoids, and lateral cricoarytenoids. As a result, increased subglottal pressure is required to blow the vocal folds apart, resulting in greater displacement of the vocal folds, and thus increased vocal intensity, during phonation.

Following inhalation and vocal fold adduction, exhalation begins through a process of both passive recoil forces and respiratory muscle activity. Passive recoil forces, acting on the lung-thoracic unit, are assisted by the checking action of muscles of inhalation (when recoil forces are higher than the desired subglottal pressure), or by muscles of exhalation (when recoil forces are lower than the desired subglottal pressure) (Zemlin, 1997). Checking action of inspiratory musculature during exhalation prolongs airflow to allow speech to occur, while contraction of muscles of exhalation pushes the air out to allow speech to continue.

1.1.1 Loudness in Healthy Normal Controls

Healthy normal controls possess the ability to control respiratory function during speech to increase vocal intensity. Sadagopan and Huber (2007) examined healthy normal individuals' ability to adhere to cues used to elicit increases in vocal intensity. The participants in this study were asked to read a passage under 4 different conditions; a) under their comfortable pitch and loudness, b) 10 dB above their comfortable loudness level, c) twice their comfortable loudness level and d) in the presence of multi-talker babbling noise. Results showed that in all 3 loud conditions, speakers produced significantly higher sound pressure levels (SPL) than in the comfortable loudness condition. Such increases in loudness in all three conditions were accompanied by a significant increase in lung volume excursion and abdominal volume excursion, which served as mechanisms to increase vocal intensity.

Another study by Huber, Chandrasekaran, and Woldstencroft (2005) also noted that differences in the respiratory mechanism occurred as a result of different cues to increase loudness. 30 healthy young adult controls were instructed to speak under the 4 same conditions noted in the previously-mentioned Sadagopan and Huber (2007) study while vocal intensity and respiratory kinematics, including changes in rib cage and abdominal volumes, were measured. Results revealed that speakers significantly increased their intensity under all three loud conditions, but respiratory mechanisms and musculature used to increase loudness varied depending on the desired intensity level. When targeting the 10 dB loudness level, subjects attained this intensity level by increasing the lung volume at which speech was initiated to take advantage of higher recoil pressures. However, when speaking in the twice as loud condition, such participants increased pressure of contraction of muscles of exhalation to increase pressure for speech. Additionally, in the speaking-in-noise condition, the subjects combined both of these methods, using both increased recoil pressures and expiratory muscle tension in order to obtain the desired intensity levels. Thus, it appears that healthy normal controls possess the ability to manipulate and utilize various mechanisms of the respiratory system to attain different desired vocal intensities.

Additionally, not only do healthy normal controls increase loudness by adjusting respiratory function, but also by adjusting laryngeal function. In a study by Baker et al. (2001), healthy young and older normal controls were asked to produce productions of /pae/ consisting of 5-7 syllables at three intensity levels: soft, comfortable, and loud. Measures of subglottal pressure using an intraoral pressure transducer were obtained, as was electromyographic thyroarytenoid, lateral cricoarytenoid, and cricothyroid muscle activity. Both young and old controls' subglottal pressure increased systematically from the soft to loud conditions. Additionally, both young and old controls' EMG amplitudes also increased from the soft to loud conditions, but change in the younger participants' amplitudes was more consistent/systematic.

Following review of this literature, it is evident that healthy normal controls are able to manipulate both the respiratory system and the laryngeal system in order to manipulate and achieve desired loudness levels. This now leads one to question whether PWPD are also able to perform such adjustments.

1.1.2 Loudness in PWPD

As previously noted, pathophysiology of PD has been shown to affect the function of various motor systems in the body, including the respiratory system (Wichmann & Delong, 1996). Compared to healthy age-matched controls, PWPD have been shown to have significantly lower respiratory musculature strength and intraoral pressure, which is representative of subglottal pressure during speech. This weakness in respiratory musculature includes impairments in both inspiratory and expiratory muscles, contributing to decreased expiratory flow and therefore decreased loudness (Haas, Trew & Castle, 2004). In a study by Bunton (2005), PWPD were shown to speak at lower lung volumes and with variability in lung volumes across speech compared to healthy normal controls. As a result, they also had shorter breath groups, fewer syllables per breath, shorter duration of speech per breath group, and closer lung volume initiation and termination points.

PWPD also exhibit abnormal laryngeal function as compared to healthy normal controls. A study by Hammer and Barlow (2011) conducted endoscopic, aerodynamic and acoustic assessment of respiratory and phonatory control to examine whether PWPD exhibited abnormal laryngeal somatosensory function compared with healthy normal controls. After taking a full breath, participants were asked to repeat the syllable /pa/ at a rate of two syllables per second at their comfortable pitch and loudness levels. Air pressure was then measured during the closed mouth phase of /p/ as representative of estimated subglottal air pressure, and expiratory airflow was measured through a pneumotachograph. Results indicated that, compared to healthy normal controls, PWPD had significantly decreased subglottal air pressure, laryngeal resistance, peak expiratory airflow, and lung volume extended for each syllable (Hammer & Barlow, 2011). Additionally, these participants also exhibited decreased vocal intensity compared to normal controls (Hammer & Barlow, 2011).

Healthy normal controls also exhibit greater subglottal pressure and higher expiratory flows during speech compared to persons with PD, and demonstrate the ability to manipulate these characteristics to adjust vocal intensity (Hammer & Barlow, 2011; Sadagopan & Huber, 2007; Baker et al., 2001). Following examination of typical respiratory function in both healthy normal controls and PWPD, this paper will transition toward examining whether PWPD are able to manipulate vocal intensity as well.

1.1.3 Means to Manipulate Loudness

Though PWPD have been shown to have decreased loudness as compared to healthy normal controls, several studies have shown that PWPD are able to increase loudness through adjusting both respiratory and laryngeal functioning. In a study by Spielman et al. (2011), 12 participants with idiopathic PD were assigned to receive Lee Silverman Voice Training (LSVT ® LOUD) (Ramig, 1995), a behavioral treatment used to treat speech and voice. LSVT trains healthy vocal loudness by encouraging speakers to "think loud" (Ramig, 1995). 4 of the participants underwent subthalamic nucleus deep brain stimulation (STN-DBS), and were placed into the LSVT group, while the remaining 8 participants were placed in either LSVT or in the untreated control group. Individuals were trained to improve vocal fold adduction as well as laryngeal muscle activation and control, thereby serving to increase subglottal pressure and therefore increase intensity levels (Ramig, 1995). Results showed that both of the PD-LSVT treatment groups showed significant increases in their intensity levels as compared to the control group.

Additional measures used to increase loudness in PD include magnitude production scales, wherein individuals are asked to speak at varying degrees of loudness, including comfortable loudness, 10 dB above comfortable, twice as loud as comfortable, in the presence of background noise, etc. (Darling & Huber, 2011; Huber & Chandrasekaran, 2006). In a study by Darling and Huber (2011) using such magnitude production scales, during an extemporaneous speech condition PWPD significantly increased intensity levels in the loud conditions as compared to the comfortable loudness level, just as the healthy normal controls did. However, during the reading tasks, PWPD produced significantly lower vocal intensity levels than healthy normal controls. Stathopoulos (2012) also found that PWPD significantly increased their vocal intensity while speaking in noisy environments as compared to quiet, a phenomenon known as the Lombard effect. Changes in laryngeal and respiratory function also were observed, with estimated subglottal air pressure significantly increasing, and higher lung, ribcage, and abdominal volume ranges.

Though various studies utilizing both behavioral treatment and magnitude production scales have found PWPD to increase vocal intensity following treatment, it has been found that PWPD do not as a rule increase vocal intensity to the levels produced by healthy normal controls. As noted in the Darling and Huber (2011) described above, though PWPD significantly increased vocal intensity during extemporaneous speaking conditions as compared to healthy normal controls, this increase was not evident during a reading task.

Now that PWPD have been shown to possess the ability to increase vocal intensity through manipulations in the respiratory and laryngeal systems, this leads one to question whether precision of articulation in PWPD may change in a manner similar to that of healthy normal speakers. This paper will now transition towards examining articulation in both healthy normal controls and in PWPD.

1.2 Articulation Production Background

Acoustic properties of speech change overall in Parkinson's disease, characterized by both imprecise consonants and vowels (Antolik & Fougeron, 2013; Sapir et al., 2007). While production of both consonants and vowels is impaired in PWPD, many objective methods of measuring articulatory precision in Parkinson's disease center around vowels. Thus, this paper focuses on measuring articulatory precision through use of acoustic properties of vowels, and for this reason examination of articulatory function in PWPD will focus primarily on articulation of vowels.

Recognition of vowels is dependent upon the acoustic properties of that sound, specifically, vowels' formant frequencies (Stilp & Assgari, 2019). Every vowel is distinguished from others by the relationship between the first (F1) and second (F2) formant frequencies (Sapir, 2010). These formant frequencies change in predictable ways as a result of movement of the articulators and resulting changes in vocal tract configuration (Sapir, 2010). In other words, by placing the tongue in varying locations within the oral cavity, different values for the first and second formant frequencies are produced (Sapir, 2010). Generally, the value of F1 changes based on tongue height, while the value of F2 changes based on tongue "forwardness." For example, when the tongue moves forward in the oral cavity to produce /i/, the value of F2 increases, and when the tongue moves further back in the oral cavity to produce /u/, its value decreases. However, as the tongue must be positioned high in the oral cavity to produce both /i/ and /u/, the two vowels have a similar F1 value. Therefore, the difference in tongue forwardness is what allows individuals to produce /i/ vs. /u/, and the resulting difference in F2 values is what allows listeners to differentiate between the two vowels (Sapir et al., 2007; Sapir et al., 2010).

Lindblom (1990) claimed speech ranges on a continuum from hypoarticulate to hyperarticulate speech. Lindblom noted that hyperarticulate speech is characterized by greater displacement of the articulators, and is generally evident during loud speech. When one increases the displacement of articulators during production of a vowel, this results in a greater difference between the formant frequency values serving to characterize that specific vowel and differentiate it from others. This enhances the difference between that vowel and others perceptually, therefore making the speech both clearer and more distinctive (Sapir, 2010; Tjaden & Wilding, 2014; Lindblom, 1990). Therefore, the term 'distinctive speech' used throughout this paper refers to vowels which are able to be perceptually identified and differentiated from others with ease.

As compared to hyperarticulate, hypoarticulate speech is characterized by reduced movement of the articulators, resulting in closer formant frequency values between different vowels, decreased articulatory precision and distinctiveness, and subsequently compromised clarity of speech (Sapir et al., 2010; Lindblom, 1990). Therefore, because all formant frequency values are reduced and produced within a smaller range, it becomes difficult to distinguish one vowel from another (Sapir et al., 2010). For example, if the tongue does not move back far enough in the oral cavity to produce an /u/, the value of F2 will be higher than normal for the /u/, and may have a value closer to the F2 of /i/. This results in less clear, less distinctive speech.

With increased displacement of the articulators comes greater disparity between the first and second formant frequencies, therefore resulting in more distinctive, clear speech. Transitioning from examination of clear speech production, this paper will now examine differences in articulation between healthy normal controls and PWPD.

1.2.1 Articulation in Healthy Normal Controls

Lam, Tjaden, and Wilding (2012) examined healthy normal controls' ability to increase the clarity of articulation during speech. 12 healthy normal controls were instructed to read sentences from the Assessment of Intelligibility of Dysarthric Speech (AIDS), and were instructed to speak in four different manners: habitual speech, clear speech, speech one would use when speaking to a hearing-impaired individual, and over-enunciated speech. Vocal intensity was obtained and articulation precision was measured using the Vowel Space Area (VSA). Results showed that vocal intensity increased in each of the clear, hearing-impaired and over-enunciated conditions, and that the vowel space area was significantly greater for all three conditions compared to habitual, representing increased articulatory precision. Results showed that when healthy normal controls attempt to speak clearly, loudness levels increase and as a result, so does articulatory precision.

A study by Lam and Tjaden (2013) also examined the relationship between clear speech and sentence intelligibility, the degree to which speech produced by an individual is able to be easily understood by the listener. Healthy normal speakers were instructed to produce sentences in four different speaking conditions: habitual, clear, hearing impaired, and overenunciate. Percentage-correct intelligibility scores and proportion of content words produced correctly were calculated for each of the four conditions, as well as vocal intensity. Results revealed that for ten of the speakers, the overenunciate condition was associated with the greatest intelligibility scores, compared to the habitual condition. The hearing-impaired and clear conditions received the next greatest intelligibility scores. The researchers concluded that instructing healthy individuals to speak clearly results in increased intelligibility of speech. Though the researchers did not examine whether vocal intensity increased as a function of speaking condition, as previously noted, as a result of speaking clearly, individuals tend to increase vocal intensity and articulatory precision, as evidenced by greater disparity between F1 and F2 values (Lam, Tjaden, & Wilding, 2012). Thus, by attempting to speak clearly, participants likely may have increased vocal intensity, which led to more precise articulation, and thus increased speech intelligibility.

1.2.2 Articulation in PWPD

Most types of dysarthria, including hypokinetic, are characterized by reduced range of articulatory movements, such that the intended place and degree of vocal tract constriction are not fully achieved (Kent & Kim, 2003). A study by Walsh and Smith (2012) compared articulatory and kinematic movement in PWPD to healthy age and sex-matched controls. PWPD and age and sex-matched healthy normal controls read sentences containing predominantly bilabial consonants ten times using their natural speaking voice. Articulatory lip and jaw movement were collected with a Northern Digital Optotrak 3020 system (Waterloo, Ontario, Canada), and the acoustic speech signal was recorded with a microphone. Measures of displacement and velocity were also obtained. Between-group differences revealed that PWPD had significantly smaller lower lip and jaw displacement, as well as lower lip and jaw velocity, as compared to healthy normal controls (Walsh & Smith, 2012).

This reduced range of motion evident in PWPD impacts both consonants and vowels. Consonants tend to be imprecise, and vowels tend to be centralized. When centralized, vowels that have high formant frequencies tend to have lower formant frequencies, and vowels that have low formant frequencies tend to have higher formant frequencies, leading vowels to be less distinctive and precise (Sapir et al., 2007; Lam, Tjaden, & Wilding, 2012). A study by Whitfield and Goberman (2014) compared articulation of PWPD and healthy normal controls using one measure of articulatory precision, the articulatory-acoustic vowel space area (AAVS), which is measured by calculating the Euclidean distances between the F1 and F2 coordinates of the corner vowels /i/, /u/, /a/ and /ae/ in the F1-F2 plane (Sapir et al., 2010). The researchers found that articulation precision was significantly lower in the PWPD group as represented by decreased listener ratings of speech clarity, as well as by a decreased AAVS measure, a measure of articulatory precision

(Whitfield & Goberman, 2014). A study by Skodda, Visser and Schlegel (2011) also calculated the F1 and F2 values from vowels /a/, /i/, and /u/ extracted from words read aloud from a text by both individuals with PD and healthy age-matched speakers. The researchers then calculated the triangular Vowel Space Area (tVSA) and Vowel Articulation Index (VAI), both also measures of articulatory precision. Results revealed that, compared to healthy normal controls, VAI values were significantly reduced in both males and females with PD, while tVSA values were reduced only in male PWPD. Furthermore, in the previously-mentioned Walsh and Smith (2012) study, F2 slopes calculated from production of the words “boy” and “moist” revealed significantly reduced slopes compared to normal speakers, reflecting reduction in the rate of change in the oral cavity.

1.2.3 Means to Measure Acoustic Characteristics of Vowel Articulation

Various means have been used to measure articulation precision of vowels in both healthy normal controls and PWPD. One method includes the Formant Centralization Ratio (FCR), which calculates vowel centralization using the formula (F2u+F2a +F1i+F1u)/(F2i+F1a) (Sapir et al., 2010). Another established method is the Vowel Space Area (VSA), which is measured by calculating the Euclidean distances between the F1 and F2 coordinates of the corner vowels /i/, /u/, /a/ and /ae/ in the F1-F2 plane, essentially measuring the perimeter of this area (Sapir et al., 2010; Whitfield & Gobermann, 2014). Yet another measure includes the triangular Vowel Space Area (tVSA), which calculates the Euclidean distances between the F1 and F2 coordinates of the corner vowels /i/, /a/, and /u/ in the F1-F2 plane (Skodda, Visser & Schlegel (2011). An additional measure includes the lnVSA, which is very similar to the VSA, with the exception of the formant frequencies being scaled with a natural log (Ln) before the VSA is constructed (Sapir et al., 2010). Finally, measurement of the F2 ratio can be performed, wherein a ratio of the second formant frequency of /i/ to the second formant frequency of /u/ is calculated to gather an idea of articulation precision. This method is sensitive to movements affecting these formant frequencies, such as anterior-posterior movements of the tongue, and rounding and un-rounding of the lips, and the ratio should increase with articulatory precision and decrease with articulatory undershoot (Sapir et al., 2010).

A study by Sapir et al. (2010) compared the VSA, lnVSA, FCR and F2i/F2u in order to evaluate each measure's ability to effectively differentiate between normal and dysarthric speech. PWPD and age- and gender-matched healthy normal controls produced multiple repetitions of sentences. Each sentence was recorded via microphone and was digitized to a computer using Goldwave software and Kay Elemetrics Inc. CSL software. Results showed that the VSA failed to differentiate between dysarthric and nondysarthric individuals, and that the lnVSA differentiated only partially between the groups. However, Sapir et al. (2010) found that the FCR and F2i/F2u both significantly differentiated dysarthric from nondysarthric speech. Additionally, the study noted that, due to the high reliability between the two measures, the FCR may be superfluous, as it involves more calculations regarding more formants.

Whitfield and Gobermann (2014) also found the Articulatory-Acoustic Vowel Space (AAVS) to significantly differentiate between articulation of persons with dysarthria and healthy normal controls. A study by Weismer et al. (2001) also failed to find a significant difference in the VSA of PWPD as compared to healthy normal controls, despite PWPD being perceived as less intelligible by listeners. Additionally, in the previously-mentioned Skodda, Visser and Schlegel (2011) study, the tVSA exhibited difficulty in identifying imprecise vowel articulation between genders in PWPD as compared to the VAI.

1.3 Changes in Articulation with Changes in Loudness in Healthy Normal Controls

Increases in vocal intensity produced by healthy normal controls have been shown to be accompanied by increases in articulatory precision. In a study by Huber and Chandrasekaran (2006), healthy young adults produced two sentences at the same intensity levels as the Sadagopan and Huber (2007) study. Lip and jaw kinematics were measured using algorithms run in the program MATLAB (Moler, Little, & Bangert, 1984) and the first and second formant frequencies were measured using a Fast Fourier Transform. Results showed that the mean first formant significantly increased in the loud conditions as compared to the regular speech conditions, as did the second formant in the 10 dB+ condition. Such an increase in sound pressure level (SPL) resulted in an increase in the velocity and displacement of the articulators as well, leading to larger formant values representing more precise and distinctive articulation.

Whitfield, Dromey and Palmer (2018) found similar results using different indirect measures of articulation precision. Healthy young adults were instructed to repeat two sentences ("It's time to shop for two new suits; A good AC should keep your car cool") at three loudness levels: soft, comfortable, and loud. The triangular VSA was then calculated using average F1 and F2 values comprising /i/, /u/ and /a/ for the vowel, and the AAVS was calculated using F1 and F2 values as well. Results showed that vocal intensity significantly increased across the varying loudness conditions, and that such increases were accompanied by significant increases in both the VSA and AAVS, representing more precise and distinctive speech.

It is important to note that increases in formant frequencies have not always been shown to consistently accompany increases in vocal intensity. As compared to the findings of Huber and Chandrasekaran (2006) and Whitfield, Dromey and Palmer (2018), Koenig and Fuchs (2019) found that naturalistic loud speech in healthy normal speakers did not consistently lead to changes in formant frequencies. Healthy participants were instructed to speak both softly and loudly in three varying tasks: 1) reading sentences containing vowels /i/, /u/ and /a/ 2) answering questions 3) a recipe recall task wherein participants were required to read various recipes for pizza. F1 and F2 were measured as the midpoint of each vowel, and were then used to compute the VSA as an indirect measure of articulatory precision. Results revealed that participants increased vocal intensity across all three tasks. However, a reduced VSA during the recipe recall task was seen as compared to the tasks involving answering questions and reading. Additionally, the value of F1 did not significantly increase between normal and loud conditions for high, tense vowels such as /i/ and /u/, but did for low, lax vowels such as /a/. However, this is expected, as though F1 is related to tongue height, and during production of /i/ and /u/, tongue height does not vary. Researchers also found that F2 did not change significantly with loudness alone, but rather with tenseness, changing greater during production of tense vowels (/i/ and /u/) than lax, a result also anticipated due to the fact that F2 changes with changes in tongue "forwardness", which changes during production of /i/ and /u/. Additionally, results examining the effect of vocal intensity on VSA showed the VSA increased significantly following increases in loudness.

Healthy normal controls have been shown to possess the ability to increase vocal intensity through use of typical physiology used to do so. Furthermore, these increases in loudness are accompanied by changes articulatory precision, resulting in more precise, and thus more easily discernible, speech (Huber & Chandrasekaran, 2006; Sadagopan & Huber, 2007; Whitfield, Dromey, & Palmer, 2018). Thus, by speaking loudly and more precisely, healthy normal speakers are able to increase the clarity and intelligibility of their speech. Now this brings one to the question: can PWPD do the same?

1.4 Changes in Articulation with Changes in Loudness in PWPD

Various studies have noted that PWPD are able to change their loudness, and with these changes in loudness come changes in articulation. As previously noted, PWPD typically speak with lower vocal intensities than healthy normal controls (Haas, Trew & Castle, 2004). In a study by Sapir et al. (2007), 14 PWPD receiving LSVT, 15 PWPD not receiving LSVT, and 14 age-matched healthy normal controls were instructed to repeat a series of phrases both pre-and post-treatment. Acoustic recordings of the productions were obtained, and were digitized to a computer using Goldwave software. Vowels /i/, /u/ and /a/ were extracted from the phrases, and measurements of the tVSA were completed. Two speech-language pathologists and four graduate students in speech-language pathology also rated vowel "goodness," which was defined as whether the vowel was a good exemplar of the target vowel. Pre-treatment, F2 of /u/ and the F2i/F2u ratio differed between the persons with PD and healthy individuals. However, results revealed that post-treatment, the F2i/F2u ratio significantly increased in the PWPD group receiving LSVT (and speaking with greater vocal intensity) as compared to the PWPD non-LSVT group and healthy age-matched controls. Additionally, accompanying this increase in the F2 ratio were better vowel ratings; the post-treatment vowels were also rated as better exemplars of the target vowel as compared to pre-treatment vowels.

A study by Spielman et al. (2011) also showed that following Lee Silverman Voice Training (LSVT), PWPD showed significant increases in articulation precision as measured by a Voice Articulation Index (VAI) (Spielman et al., 2011). Four PWPD receiving STN-DBS were assigned to a group receiving intensive voice treatment, while 8 participants not receiving STN-DBS were placed in either LSVT or an untreated control group. All participants were instructed to read the Rainbow Passage aloud, describe a picture, repeat a sentence ten times, and speak about a self-selected topic for one minute. Vowels were extracted from each sentence, and the VAI was then constructed. Results showed an increase in VAI from pre- to post-treatment for the LSVT-DBS group but not for the LSVT or no treatment group. However, researchers noted that articulatory precision of the LSVT-DBS group was significantly worse (as measured by VAI administered prior to the study) than the LSVT group prior to treatment, which may have left more room for such individuals to make improvement.

Additionally, in the previously-mentioned study by Huber and Chandrasekaran (2006), higher vocal intensities were elicited during speech using varying loudness cues; such increases in intensity were accompanied by increased articulation precision, with larger displacement and faster velocity of articulators.

1.5 Grant Purpose

As noted above, disturbances in speech noted in Parkinson's Disease stem from disruptions in basal ganglia control circuit functioning (Wichmann & DeLong, 1996; Duffy, 2013). Currently, little information is known regarding the role of basal ganglia participation in speech production. However, discovery of its role may serve to provide important information necessary for the development of treatments for speech deficits associated with such movement disorders (Project information, n.d.). The proposed research study is part of a larger NIH-funded study to investigate "how motor and linguistic speech information is encoded within the STN-cortical network, and to determine the relationship between neural activity within the STN-cortical network and the gain of vocal output" (Project information, n.d.).

1.6 Research Questions and Hypotheses

PWPD tend to have poor articulatory precision due to reduced range of articulatory movements (Kent & Kim, 2003). These persons also tend to speak with reduced vocal intensity due to reduced respiratory muscle strength and reduced vocal fold adduction (Haas, Trew & Castle, 2004). However, similar to healthy normal controls, research has shown that PWPD show increasing articulatory precision with increasing vocal intensities (Haas, Trew & Castle, 2004; Spielman et al., 2011; Sapir et al., 2007; Huber & Chandrasekaran, 2006). This research will explore the ability of PWPD, undergoing DBS surgery of the STN, to increase speech intensity and articulatory precision during the repetition of 3-syllable sequences presented at soft and loud levels. The specific research questions are:

1. Are the vowel intensities produced by patients significantly higher for the loud stimulus presentation condition compared to the vowel intensities produced for the soft presentation condition?
2. Are the F2 ratios produced by patients significantly larger for the loud stimulus presentation condition compared to the F2 ratios produced for the soft stimulus presentation condition?

It is hypothesized that patients will increase vocal intensity when cued with a louder stimulus, and that such changes will result in an increased F2 ratio.

While this specific research study will not necessarily provide novel findings regarding the relationship between vocal intensity and articulatory precision in PWPD, these results should replicate earlier findings in an intra-operative environment, and will be used within the context of the larger study to determine the relationship between neural activity within the STN-cortical network (via recording of STN units, and STN and cortical local field potentials) and the gain in vocal acoustics of speech production during DBS surgery (Project Information, n.d.). This study additionally may provide insight into the role motivation plays when increasing articulatory precision.

2.0 Methods and Procedure

The data analyzed in this study have been collected previously as part of a larger research study examining the role of the subthalamic nucleus (STN)-cortical network on motor and linguistic speech production. The role of the STN in the motor system has been implicated from various studies performing DBS on the STN of PWPD; however, its role in speech, as well as a neurophysiological model for its role, has yet to be fully explored and clearly defined (Project Information, n.d.). Thus, the aim of the larger study was to examine how both motor and linguistic speech information are encoded within the STN-cortical network, as well as to explore the relationship between neural activity within the STN and vocal output gain (Project Information, n.d.). The study's aims were motivated by a desire to formulate a model of the STN's role in speech production to aid in developing treatment for speech impairments experienced by PWPD.

To target study aims, PWPD were recruited to participate in this study while they were undergoing DBS surgery. During the surgical procedures, once recording electrodes were placed in the STN and relevant cortical areas, participants were awoken to perform the speech production task intraoperatively, and neural activity within the STN-cortical network, cortical local field potentials (LFP), and speech acoustics were obtained. Due to data collection occurring intraoperatively, limited control over some aspects of data collection was available, leading to certain undesirable methods of data collection as well as study design to characterize the study. For example, as the study was performed and data were collected within an operating room, background noise produced during the operative procedures was unable to be controlled for or eliminated. This may have interfered with the acoustic signals recorded during the operation for later analysis. Due to time and technology constraints created by the surgical context, the intensity of the recorded acoustic signal was uncalibrated. Furthermore, as DBS is performed solely on persons with movement disorders, the study did not include a control group. The design of this study is a within-subject experimental design.

2.1.1 Participants

Participants consisted of 16 PWPD who presented to a neurosurgical clinic for DBS. 9 participants were male, 7 participants were female. All participants were between the ages of 52-80. Scores on the motor portion of the Unified Parkinson Disease Rating Scale (UPDRS) for all participants while off of their dopaminergic medication ranged from 6-50. All participants were native English speakers, had a diagnosis of idiopathic Parkinson's disease, had been recommended for surgical treatment for PD, and had favorable anatomy for DBS. Four participants had been diagnosed with a cognitive impairment as determined by medical history obtained for each participant. No participants had been diagnosed with dyspnea, dysarthria, or voice disorders, and all participants underwent pure tone hearing screenings at 500 Hz, 1kHz, 2 kHz, and 4kHz at 25 and 40 dB HL.

All PWPD participating in the study underwent intraoperative DBS, and received medical approval to do so. All research procedures were approved by the University of Pittsburgh Institutional Review Board (IRB Protocol # PRO13110420), and all participants provided informed consent to participate in this study. All participants were off their medication 12 hours prior to the surgical procedure. Demographic information for each individual participant is found below in Table 1.

Table 1: Participant Demographic Information

Participant #	Age	Gender	Years since diagnosis	UPDRS Score
1	69	female	9	45
2	79	male	1	34
3	64	female	2	21
4	74	male	7	40
5	66	male	9	19
6	52	female	5	6
7	69	male	5	38
8	64	male	3	30
9	65	female	5	37
10	77	female	4	22
11	71	male	9	50
12	59	male	4	33
13	66	female	5	39
14	80	male	Not reported	Not reported
15	64	female	9	43
16	72	male	5	39

2.1.2 Data Collection/Speech Tasks

Three- syllable pseudowords (triplets) were created using a total of 12 consonant-vowel (CV) syllables. Triplets were presented auditorally to the participants. To develop the stimuli, CV syllables were formed from consonants /g, t, s, v/ and vowels /i, a, u/. Syllables formed included /ga, gi, gu, sa, si, su, ta, ti, tu, va, vi, vu/. All 12 CV syllables were recorded by a male speaker using normal voice. Following recording, the duration of each CV syllable was equated at 500 ms (Praat PSOLA script) (Boersma & Weenink, 2020). The 12 CVs were then partially randomly combined into triplets (i.e. ga/vu/ti) using a semi-stochastic procedure. Triplets were formed such that each of the 12 CVs appeared in each syllable position (i.e. initial, medial, final) 10 times within each list, and were equally represented. The resulting triplets were then used to create five lists, with 60 triplets per list. Pratt (ScaleIntensity_script) was used to scale the intensity of the triplets, in order to create a sufficient contrast between soft and loud conditions (that is, uncalibrated levels within Praat of 50 and 75 dB). The order of soft and loud conditions within each list was partially randomized, but were presented in a fixed order to each participant.

During preoperative procedures, instructions were provided on the speech production task. Using ear inserts, participants were presented with auditory stimuli and instructed to repeat each triplet at a vocal intensity that matched the loudness level of the stimulus. Practice was provided in order to ensure task comprehension and receive redirection regarding changes in vocal intensity. The presentation level of the acoustic stimuli was adjusted for each patient so that the soft signal was increased to a level which was comfortably audible and perceived as soft (Cox & Gray, 2001).

In the operating room, following the initial placement of an electrode array within the STN, the supine participants were awoken from general anesthesia and instructed to repeat each triplet at the perceived loudness level, similar to the preoperative training procedures. The order of the triplets remained consistent when presented to each participant. During experimental data collection, the electrode array was moved to different recording depths within the STN and the speech task was repeated at each depth. This corresponded to 2-4 sessions of speech tasks, depending on surgical concerns and participant fatigue.

2.1.3 Instrumentation

The triplet stimuli were presented to patients through an audio amplifier (PreSonus, AudioBox iTwo) via ER38-14F foam tip ear inserts (Etymotic Research, Inc.) The microphone (AT875R, Broadcast & Production Microphones) was positioned at a mouth-to-microphone distance of 15 cm, 45 degrees below the horizontal level of the left oral angle. The acoustic data were digitized at 44.1kHz with a 7.5 kHz low-pass anti-aliasing filter (H6 Handy Recorder, Zoom Inc.) Due to restrictions of the intraoperative environment, the acoustic speech signal obtained from the microphone was uncalibrated. However, since intensity data was analyzed within-subject, amplitude settings and background noise should be similar within a participant.

2.1.4 Acoustic Analyses and Measurements

Acoustic analysis of recordings first were completed utilizing MATLAB 2017a (Mathworks Inc., Natick, MA, USA), R version 3.4. 4 (R Development Core Team, 2018). Acoustic signals were displayed in MatLab as spectrograms with a customized graphical user interface (GUI) to allow for detailed marking of consonants and vowels, voice and transcription of speech. The onset and offset of each vowel within each triplet were marked to aid in later calculation of the F2 ratio and vowel intensity. The offset of each vowel was identified and marked at the end of consistent glottal pulses, which represent vocal fold vibration. Vowel onsets were marked differently, depending on whether the vowel was preceded by a voiced or voiceless consonant. When preceded by a voiceless consonant, the onset of the vowel was marked at the origin of glottal pulses; when preceded by a voiced consonant, the onset of the vowel was marked at the onset of the vowel's first formant structure. The author was involved in portions of the above acoustic analysis prior to involvement in this study; however, reliability data for these measurements are not available at this time.

Perceptual judgments of the accuracy of vowel productions were then completed. This was done to analyze whether participants correctly produced the vowels within the triplets presented auditorally to them. 3 participants were randomly selected, and 20 productions across each participant's session were compared to the intended targets. Across the 3 sessions, 94.5% of vowel productions matched the intended target. During subsequent analyses, only productions of vowels /i/ and /u/, rather than close approximations (/I/ and /ʊ/) were included in calculations of intensity, F2 values, and F2 ratios.

Following analysis of production accuracy, a custom script was then used to automatize extraction of average intensity and second formant (F2) values of each /i/ and /u/ vowel in each utterance based on the previously-made markings. The average intensity (in uncalibrated units) for each /i/ and /u/ vowel production was calculated through a custom acoustic intensity script in Praat. The script used time points that were collected by research assistants (described above) from the onset, offset, and duration of each vowel in each utterance. Then, the script used the vowel duration to calculate acoustic intensity using the Praat "energy" method ($10 \log_{10} \{1/(t_2 - t_1) \int_{t1}^{t2} 10^{x(t)/10}\, dt\}$). For each utterance, the intensities of the vowels /i/ and /u/ were averaged to represent the intensity for that utterance. Second formant values were identified within Praat by automatically selecting the middle 1/3 of each vowel in order to capture the second formant's steady state, defined by Zemlin (1997) as periods of a time during production of a tone wherein the frequency, amplitude, and phase of the tone are constant. Throughout extraction of F2 and intensity values for each utterance for each participant, values were selected at random to be manually checked to ensure each value's accuracy and to ensure the script was properly working. To examine articulatory precision, the F2 ratio then was calculated by dividing the formant frequency for /i/ by the formant frequency for /u/ within each triplet utterance.

2.2 Statistics

After obtaining intensity and F2 ratios for all utterances produced by each participant, in both soft and loud stimulus conditions, statistical testing was performed. The design of this study was a within-subject experimental design. Prior to conducting statistical testing, analyses were completed to analyze for normality of the data. This consisted of creating histograms for the vowel intensity data in both soft and loud conditions. Additionally, measures of skewness and kurtosis were completed in Excel.

If the intensity data were demonstrated to be normally distributed and parametric, one-way paired t-tests would be performed to analyze whether intensity significantly increased across conditions. If intensity significantly increased across conditions, one-way paired t-tests would then be performed examining whether this significant increase was also observed in the F2 ratio.

If the data were determined to be nonparametric, a Wilcoxon Signed-Rank Test (for paired data) would be performed to examine whether vowel intensities produced by the patients were significantly larger in the loud condition as compared to the soft. If a significant increase was evident in the loud condition, a Wilcoxon Signed-Rank Test would then be performed to analyze whether this increase occurred in the F2 ratio as well. Using the Bonferroni correction, the alpha level was set at $p<0.025$. An online statistical calculator (N. Vasavada, 2016), using R code, was used for statistical analysis.

2.3 Results

The first aim of this study was to examine whether persons with Parkinson's disease were able to increase their vocal intensity when instructed to do so via presentation of a loud versus soft stimulus. If significant increases in intensity were observed, an additional aim of the study was to examine whether these increases in intensity were accompanied by an increase in the F2 ratio, which would be indicative of increased articulatory precision.

Mean intensities and F2 ratios for individual participants, as well as the group means, are listed below in Table 2. Descriptively, the group means for vocal intensity demonstrated an increase between the soft and loud conditions. This increase also was observed for 13 out of 16 individual participants, with mean vocal intensity increasing in the loud as compared to the soft condition. Contrary to these 13 participants, 3 participants' (P1, P4 and P7) mean vocal intensities decreased in the loud as compared to the soft condition.

The observed mean increase in vocal intensity for the group was accompanied by a mean increase in the F2 ratio. However, this increase was observed only in 10 individual participants. 5 participants demonstrated a decrease in the F2 ratio in the loud compared to the soft condition. One participant's F2 ratio did not reflect a change across soft and loud conditions, but rather remained stable. Of the 6 participants whose F2 ratios did not increase, 2 of those participants did not demonstrate an increase in intensity, which was not surprising. The remaining four participants did exhibit an increase in intensity across the soft and loud conditions, but their F2 ratio did not increase.

Table 2: Means (and Standard Deviations) for Vowel Intensity and F2 Ratios, and Spearman Rho Correlations between Intensity and F2 Ratio

	Mean Vowel Intensity (and SD) (uncalibrated dB)		Mean F2 Ratio (and SD)		Spearman Rho Correlations between Intensity and F2 Ratio	
Participant	**Soft Condition**	**Loud Condition**	**Soft Condition**	**Loud Condition**	**R_s**	**p-value**
1	75.66 (0.44)	75.52 (3.87)	1.28 (0.39)	1.32 (3.68)	0.28	0.00044
2	80.12 (0.32)	84.04 (3.68)	1.33 (0.28)	1.31 (3.68)	-0.08	0.29737
3	68.49 (2.65)	77.52 (3.04)	1.52 (0.43)	1.62 (0.46)	-0.01	0.80922
4	69.81 (1.64)	65.39 (4.20)	1.95 (0.44)	1.78 (0.37)	0.32	0.00002
5	53.64 (1.69)	58.97 (1.30)	1.49 (0.39)	1.81 (0.42)	0.45	0.45605
6	70.83 (1.57)	71.43 (1.49)	2.17 (0.45)	2.27 (0.47)	0.15	0.14626
7	77.04 (4.51)	76.14 (5.05)	1.39 (0.47)	1.25 (0.47)	-0.04	- 0.04981
8	75.08 (1.84)	77.18 (2.34)	1.36 (0.31)	1.32 (0.28)	0.06	0.06482
9	74.92 (1.55)	78.08 (1.84)	1.52 (0.33)	1.53 (0.34)	0.33	0.33637
10	70.89 (4.48)	76.61 (1.61)	1.89 (0.58)	2.13 (0.47)	0.29	0.29228
11	70.92 (2.70)	74.20 (1.84)	1.22 (0.20)	1.30 (0.14)	0.18	0.18700
12	66.31 (2.98)	67.76 (4.00)	1.32 (0.24)	1.36 (0.28)	0.13	0.13180
13	69.56 (1.48)	73.06 (2.07)	1.58 (0.26)	1.68 (0.22)	0.39	0.39406
14	76.96 (5.07)	77.80 (4.26)	1.68 (0.35)	1.60 (0.34)	-0.25	- 0.24959
15	70.01 (2.49)	70.99 (2.69)	1.18 (0.21)	1.20 (0.25)	0.12	0.12906
16	74.50 (7.68)	78.42 (6.28)	1.15 (0.16)	1.15 (0.11)	0.22	0.22489
Group	**71.55 (6.06)**	**73.94 (6.02)**	**1.50 (0.29)**	**1.54 (0.33)**		

Prior to statistical testing, the data were analyzed to examine normality of the data. Histograms for intensity in both conditions were completed across participants. These results are presented in Figure 1 below.

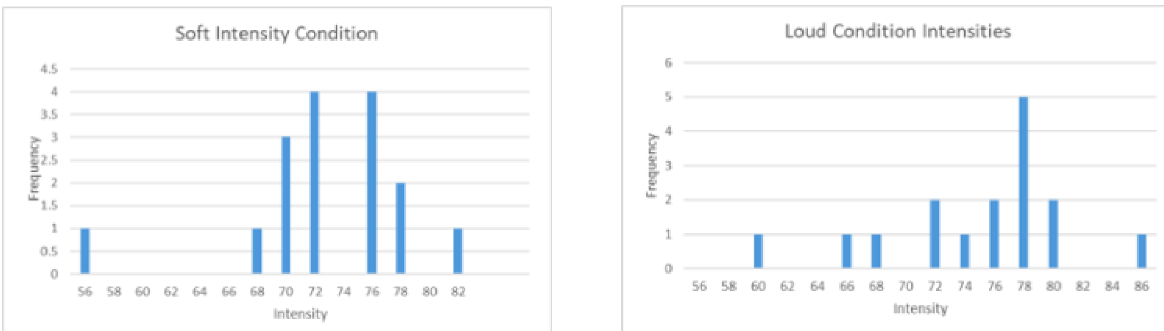

Figure 1: Intensity Histograms for Soft and Loud Conditions

Based on visual inspection of the resulting histograms, the intensity data did not appear normally distributed, but rather, were negatively skewed. Measures of skewness and kurtosis were then computed, to support the inspection of the histograms. Measures indicated that the soft and loud conditions were both negatively skewed, while kurtosis was leptokurtic for both the soft and loud conditions. Measures of skewness and kurtosis for intensity data in both conditions are listed below in Table 3. Given these calculations, as well as the study's small sample size (n=16), it was determined that the data were nonparametric, and that nonparametric Wilcoxon Signed-Rank Tests should be performed.

Table 3: Skewness and Kurtosis for Group Intensity Data

	Skewness	Kurtosis
Soft intensity	-1.52	4.27
Loud intensity	-1.18	3.19

A one-tailed Wilcoxon Signed-Rank Test was performed to examine whether vowel intensities produced by the patients were significantly greater when produced in the loud stimulus condition than in the soft condition. Additionally, a one-tailed Wilcoxon Signed-Rank Test was performed to examine whether there was a significant increase in the F2 ratio for the loud stimulus condition compared to the soft condition. Using the Bonferroni correction, the alpha level was set at $p < 0.025$.

Results of the Wilcoxon Signed-Rank Tests revealed a significant increase in intensity in the loud as compared to the soft stimulus condition ($p<.00523$; $n=16$). However, there was no significant increase in the F2 ratio across the two loudness conditions ($p<.127706$; $n=16$).

Given the above F2 ratio result and examination of individual participant data, the Wilcoxon Signed-Rank Test was repeated without the three participants who failed to demonstrate an increase in average vowel intensity in the loud stimulus condition. Without these outliers, a significant increase in the F2 ratio in the loud versus the soft stimulus condition was observed ($p<.022605$; $n=13$).

Given the different statistical results of the F2 ratio with and without outliers, Spearman Rho correlations were calculated to further examine the relationship between intensity and the F2 ratio. The Spearman Rho correlations and associated p-values between vowel intensity and F2 ratio can be seen above in Table 2. Based on the interpretation of correlation coefficients provided by Dancey and Reidy (2007), 2 participants (P5 and P13) demonstrated a moderate positive correlation between intensity and the F2 ratio. These correlations are displayed on scatterplots provided below. For 10 participants there was a weak correlation. For the remaining 4 participants (P2, P3, P7 and P8), there was no correlation between intensity and the F2 ratio.

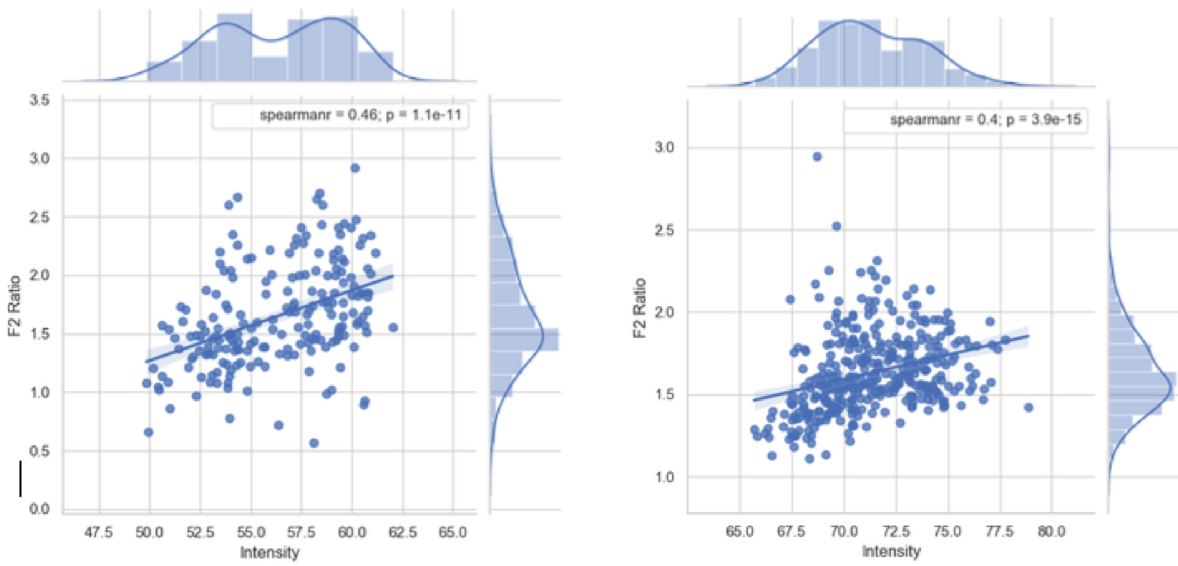

Figure 2: Participants P5 and P13 Intensity and F2 Correlations

2.4 Discussion

In healthy normal individuals, increases in articulatory precision have been demonstrated to accompany increases in vocal intensity. This also has been demonstrated to occur in PWPD, with increases in intensity leading to increases in articulatory precision (Huber and Chandrasekaran, 2006; Sapir et al., 2007; Spielman et al., 2011). Although this did not occur for every individual participant, as a group, participants in this study were able to significantly increase their vocal intensity. Due to this significant increase in group mean intensity, it was expected that group mean articulatory precision, as measured by the F2 ratio, would increase as well. However, contrary to expectations, this did not occur.

Upon inspection of individual data, it was revealed that three of the 16 participants did not increase their vocal intensity in the loud stimulus condition. As noted in the results, when these outliers were removed from analysis, a significant increase in the F2 ratio was observed. This analysis of only participants who increased their vocal intensity suggests that, when PWPD are able to increase vocal intensity, they are also able to increase their articulatory precision. Additionally, the observed ability of these PWPD to increase their vocal intensity in atypical, or even undesirable, speaking conditions (that is, during an operative procedure, whilst lying in the supine position) further supports the conclusion that these persons should possess the ability to increase their articulatory precision in typical speaking conditions as well, just as healthy normal controls (Huber & Chandrasekaran, (2006); Sadagopan & Huber, (2007); Whitfield, Dromey & Palmer, (2018)).

Mean F2 ratios obtained for each participant across soft and loud conditions in this study ranged from 1.15-2.17. These values are consistent with F2 values previously noted in the literature examining the effectiveness of the F2 ratio. In Sapir et al. (2010)'s study examining the F2 ratio in both PWPD and healthy normal controls, mean F2 values for PWPD in pre- and post-LSVT conditions ranged from 1.79 to 2.02. Similarly, these values for healthy normal controls ranged from 2.18 and 2.13. The close proximity of PWPD's mean F2 ratios in the loud condition to those of healthy normal controls suggests that, when PWPD are able to increase vocal intensity, their speech is able to become relatively precise as indicated by this ratio.

Per this study's results, increases in intensity appear to cause increases in articulatory precision. According to Narayana et al. (2010), this may be due to a top-down treatment effect speaking loudly has on the speech motor system. Narayana et al. (2010) examined the role of LSVT in increasing vocal intensity and altering neural activity in ten patients with idiopathic Parkinson's disease (IPD). Participants were instructed to read paragraphs aloud both pre and post-LSVT, and measures of cerebral blood flow and neuronal activity within neural networks were obtained. Along with a significant increase in vocal intensity post-LSVT, results of the study showed a shift in cortical activity when speaking more loudly; specifically, an increase of activity was evident in the right cortical speech motor and pre-motor systems, as well as association areas responsible for mediating multimodal integration was evident. The authors concluded that, when individuals speak loudly, activity within the cortical motor, auditory, and prefrontal areas during speech are modulated. The changes within these neural networks then serve to alter activity within the subcortical regions during speech, which serves to lead to larger articulatory movements and more precise speech (Narayana et al., 2010).

As the individual participant data are explored more closely, it is evident that the ability to manipulate vocal intensity and articulatory precision in this surgical environment was not consistent for all patients. That is, not all participants manipulated intensity and not all patients produced a change in the F2 ratio. Various explanations exist for these observations.

Certain conditions of the study may have prohibited both intensity and the F2 ratio from increasing. One potential explanation is the position in which the participants were placed throughout the procedure. For surgical purposes, participants were in the supine position. Due to the effects of gravity, this may have impacted their ability to increase intensity by prohibiting the inspiratory musculature from fully expanding the ribcage and lungs (Hixon, Weismer, & Hoit, 2020). Additionally, this positioning may have impacted their ability to move their articulators (specifically the tongue) to positions which would facilitate more precise articulation and increase the F2 ratio. Stone et al. (2007) examined the effects of the supine position on speech as compared to the upright position in healthy normal persons, and found that in the supine position, the tongue was significantly more posterior in the supine position than in the upright position. Though this did not lead to a significant difference in phonemes produced, this disparity between positions led phonemes produced by 4 participants in the supine position to vary from those produced in the upright position. As previously noted in the introduction, /u/ is produced by moving the tongue posterior in the oral cavity, while /i/ is produced with the tongue anterior in oral cavity. It is possible that the effects of the positioning and gravity facilitated participants' ability to produce /u/ by pulling the tongue posteriorly/inferiorly, but that this same positioning compromised their ability to move the tongue anteriorly/superiorly in the mouth to produce /i/. If unable to move the tongue anteriorly, this would limit the range of F2 values characterizing /i/, which would subsequently limit F2 ratio values.

The lack of significant increase observed in the group intensity and F2 ratio could also be attributed to anesthesia. Due to the surgical nature of the procedure, all participants were placed under general anesthesia for portions of the study, and were later awoken to produce the speech tasks. Known to produce cognitive side effects including delirium and confusion in the elderly in particular, the anesthesia may have compromised participants' ability to fully understand and follow the directions administered at the start of the study (Orhun et al., 2020). This may have led to intended soft productions being produced as loud, and vice versa, as well as some utterances not being produced as loudly, and therefore as precisely, as possible. This could potentially explain why, although intensities as a whole significantly increased, why the F2 ratio did not.

In addition to positioning and use of anesthesia, participant performances could also have been affected by the severity of each participant's disease process. All participants were off their medications 12 hours prior to and during the procedure; therefore, contrary to additional studies wherein PWPD were optimally medicated and deemed to be stable at the time of the study (Sapir et al., 2007), participants’ movements were not regulated or facilitated in this study. This could have compromised participants’ ability to increase their loudness to the greatest extent possible, as well as compromised their ability to increase movement of their articulators to attain more precise articulation. Additionally, per their medical records obtained prior to the start of the study, 4 of the 16 participants (P4, P5, P9, and P14) had been diagnosed with a cognitive impairment. Similar to the effects of anesthesia, a diagnosis of cognitive impairment has the potential to compromise participants’ ability to comprehend provided directions, or perceive whether the triplets presented auditorily to them were of a soft or loud intensity. This could have led to intended soft productions being produced and categorized as loud productions, and vice versa, which may have compromised results. This seems likely, as P4, one of the participants with a cognitive impairment, was one participant whose intensity did not increase.

The lack of significant increase in the group F2 ratio could also be due to perceptual difficulties experienced by PWPD. PWPD often speak with low vocal intensities, due to an inability to perceive that their vocal intensity is low (Duffy, 2005). This is attributed to difficulty PWPD experience with the integration of sensory information into motor commands. Though PWPD may have an internal desire to increase vocal intensity, this same magnitude of effort often does not manifest in motor output. This often leads to an “…altered self-assessment of loudness,” leading PWPD to believe they are speaking more loudly than they truly are (Narayana et al., 2010). However, once informed that their vocal intensity is low and after being instructed to speak more loudly, these persons are often able to increase intensity of speech (Duffy, 2005). Therefore, participants may have perceived their speech produced in the loud condition as at a high intensity, when it in fact was relatively low. This lack of the largest possible increase in intensity would limit F2 values, subsequently limiting F2 ratios.

In addition to perceptual difficulties, the lack of significant increase in group F2 may be due to a lack of motivation or incentive to be louder. In prior studies (Darling & Huber, 2011; Huber & Chandrasekaran, 2006) examining whether PWPD were able to increase both intensity of speech and precision of articulation, PWPD were provided with instructions motivating them to not simply increase intensity of speech, but also intelligibility of speech. This was achieved by instructing participants to speak loudly as if they were speaking to someone across a room, having participants speak as if they were speaking to someone in a noisy background, or actually having participants speak in a noisy background. When instructed to speak in these conditions, increases in both intensity and articulatory precision were evident, because participants were motivated to not only increase their vocal intensity, but also to enable others to perceive their speech with greater ease, which often involves becoming both louder and clearer. It is possible that incentive to be more easily understood by others plays a large role in increasing articulatory precision, and to obtain more precise speech, the inclusion of this incentive is necessary.

Various explanations also exist as to why the group F2 ratio did not increase despite a group mean increase in intensity. One potential explanation is that the observed increase in intensity simply was not significant enough to effect a significant increase in the F2 ratio. In additional studies utilizing the F2 ratio to examine articulatory precision, significant increases in intensity which effected a subsequent increase in the F2 ratio ranged between 4-13 dB SPL (Sapir, 2007). However, increases in intensity in this study ranged from 0.6 to 9.03 dB (uncalibrated units), with most increases falling around the 4.0 dB range. It is possible that, though these increases in intensity were significant, they simply were not large enough to evoke a significant increase in group articulatory precision. Additionally, the study was relatively underpowered (n=16), which also potentially contributed to the lack of significant increase in the group F2.

Another potential reason the mean F2 ratio did not increase could be due to the nature of the triplets participants were instructed to repeat. Though triplets were balanced across syllable positions such that every triplet appeared in the initial, medial, and final position at an equal frequency, the position of /i/ and /u/ were not necessarily in the same position within each utterance upon repetitions. This lack of systematic placement could have resulted in minor differences in vowel intensity.

This study was not designed solely to answer the question examined in this thesis, and as result there are certain elements one would desire to change. In this study, F2 ratios were calculated from /i/ and /u/ values within individual utterances. These individual F2 ratios were then used to compute an average F2 ratio for both soft and loud conditions for each participant. Perhaps a more effective means of analysis would involve ensuring that each individual triplet produced by participants occurred under both the soft and loud condition. Then, F2 ratios for each individual pair of utterances could be compared to examine whether there was a significant increase. As nothing would change between the two utterances except intensity, this would provide us with a much more controlled method of analysis and could provide a better indication of the relationship between intensity and the F2 ratio.

Suggestions for further research include examination of the role of motivation/incentive to increase intelligibility of speech in enhancing articulatory precision. As previously noted above, PWPD have been demonstrated to exhibit difficulty with perception of vocal intensity, which may lead these persons to produce softer speech. Various studies examining PWPD’s ability to increase intensity have done so by providing PWPD with incentives to increase intensity, with the primary incentive being to increase intelligibility of speech for listeners. In contrast to these studies, in this study PWPD were not provided with this incentive to increase intensity to enhance intelligibility, but were rather simply instructed to increase intensity. Results of the study demonstrated that, despite this lack of incentive, as a group, PWPD were still able to increase vocal intensity. Additionally, the study revealed that when participants increased vocal intensity, their articulatory precision increased as well. These findings suggest that incentive to increase intelligibility is not necessarily a requirement to increase articulatory precision, and that perhaps simply having a desire to increase intensity is sufficient to meet this goal. Further studies examining the relationship between intensity and articulatory precision without motivation or incentive would provide further insight into this relationship.

This research can also be incorporated into clinical practice. Though the literature suggests that enhancing vocal intensity in persons with poor intelligibility serves to increase articulatory precision (LSVT, PhoRTE, etc), this study provides further information about the effectiveness of these tactics in complex environments. In this study, PWPD were able to increase vocal intensity and articulatory precision despite unfavorable circumstances (supine position, under anesthesia, off medications, etc.). The knowledge that these persons are able to increase articulatory precision through increasing vocal intensity suggests that these tactics may be used in more complex environments (hospital beds, operating rooms, etc.) as well to increase intelligibility and foster better communication. Even if the speaker's vocal intensity is not low, if the listener is experiencing difficulty with the comprehension of speech, simply instructing that speaker to more greatly increase vocal intensity can be beneficial in the production of intelligible speech and the facilitation of listener comprehension.

The purpose of this study was to examine the causal relationship between vocal intensity and articulatory precision in PWPD. This was done by manipulating vocal intensity under two different conditions (soft and loud), and examining whether articulatory precision as measured by the F2 ratio increased with increases in intensity. Results revealed that, though as a group PWPD were able to significantly increase vocal intensity, this increase was not accompanied by an increase in the F2 ratio. However, when only participants who increased vocal intensity were included in the analyses, a significant increase in the F2 ratio was observed. This result suggests that, when able to increase vocal intensity, PWPD are in fact able to increase their articulatory precision.

Appendix A :Funding

Funding was provided by NINDS U01NS098969 (PI: Richardson), the Hamot Health Foundation (PI: Richardson) and a University of Pittsburgh Brain Institute NeuroDiscovery Pilot Research Award (PI: Richardson).

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