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The Effects of Deep Brain Stimulation on the Speech of Patients with Parkinson's Disease

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THE EFFECTS OF DEEP BRAIN STIMUALTION ON THE SPEECH OF PATIENTS WITH PARKINSON'S DISEASE

by

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ABSTRACT

THE EFFECTS OF DEEP BRAIN STIMULATION ON THE SPEECH OF PATIENTS WITH PARKINSON'S DISEASE

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Master of Science

Abstract

Deep brain stimulation (DBS) of the subthalamic nucleus (STN) has received more attention in recent years as a treatment option for regulating the symptoms of Parkinson's disease. Previous studies of DBS documented consistent improvements in motor function but more variability in speech outcomes. In the present study, six participants diagnosed with idiopathic Parkinson's disease who reported worsened speech with stimulation were recorded performing speech acoustic tasks with the stimulators on, and again with the stimulators off. Improvements were noted for most participants in measurements of formant slopes, long term average spectrum (LTAS) of a sustained vowel, and spirantization with stimulation on. Stimulation negatively affected most participants' vowel space area, verbal fluency, sequential motion rate, and LTAS while reading and describing a picture. Measures of stop gap duration, alternating motion rate,

and voice onset time were within normal limits for most participants across both stimulation conditions.

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Introduction

Parkinson’s disease was so named after English physician James Parkinson, who was the first to describe this “shaking palsy” in an essay he wrote in 1817. According to Duffy (2005), it has been estimated that out of 100,000 people over the age of 50, fifty are affected by Parkinson’s disease. Although no cure for the disease has been found, many treatment options are available to help manage patient symptoms. One that has received increasing attention in recent years is deep brain stimulation (DBS), a brain surgery in which electrodes are implanted into the brain to help relieve symptoms associated with Parkinson’s disease. Research has documented that electrode stimulation generally results in improved motor function, but the effect that stimulation has had on speech is more variable.

The purpose of the present study is to determine the impact of DBS on speech by analyzing a number of measures to provide information regarding rate and extent of tongue movement, spread of acoustic energy, word retrieval, and coordination of the articulators during speech. These include vowel space area, formant slopes, long term average spectrum, verbal fluency, stop closure duration, voice onset time, diadochokinetic rate, and spirantization. It is part of a larger study that will continue over the course of several years.

Overview of Parkinson’s Disease

Parkinson’s disease is a degenerative neurological disorder that primarily results from damage to the basal ganglia, leading to reduced dopamine production in a black-pigmented nucleus called the substantia nigra (Duffy, 1999). The primary form of Parkinson’s disease is idiopathic (Hoehn & Yahr, 1967), which suggests that there is no known cause for the pathology. Motor problems result when excessive activity in the subthalamic nucleus leads to an overabundance of activity in the globus pallidus interna. The excessive inhibition of the globus pallidus interna on the thalamus causes the following cardinal features of Parkinson's disease: rigidity, akinesia, and possibly tremor (Playfer & Hindle, 2001).

Characteristics of Parkinson's Disease

Motor Characteristics. There are two different types of rigidity that have been observed in patients with Parkinson's disease. *Lead pipe rigidity* refers to abnormal resistance that is continuously present when a relaxed patient's muscles are passively stretched around a joint. A ratchet-like, fluctuating type of resistance to passive movement that can be accompanied by tremor is referred to as *cog-wheel rigidity* (Meara & Koller, 2000). Akinesia was described by Playfer and Hindle (2001) as a condition in which "slowness (bradykinesia), poverty or lack of movement (hypokinesia), progressive early fatiguing and reduction in amplitude of repeated movements, impairment of sequencing or difficulty performing simultaneous motor actions" (p. 46) are commonly observed. Tremor is also a key feature of Parkinson's disease, although some patients may never develop it. Classic tremor associated with Parkinson's has a 4-6 Hz oscillation and is referred to as *resting tremor* (Meara & Koller, 2000). As the name indicates, resting tremor is most apparent when the patient is at rest, but it is absent during volitional movements. Some literature has documented that resting tremor typically begins unilaterally and distally in a limb (usually the arm), then progresses proximally in the arm, then to the ipsilateral leg, and finally to limbs of the contralateral side (Playfer & Hindle, 2001). These characteristics of Parkinson's disease may also be accompanied by the presence of festination, or a progression of normal length strides to short, rapid shuffling steps while walking (Duffy, 2005).

Speech Characteristics. Törnqvist, Schalén, and Rehncrona (2004) indicated that roughly 60% to 80% of patients with Parkinson's disease exhibit hypokinetic dysarthria; in fact, Berry (1983) suggested that 98% of all patients with hypokinetic dysarthria who are seen by speech pathologists have Parkinson's disease. Typical speech characteristics associated with hypokinetic dysarthria include a weak, breathy voice, abnormal prosody, variability in rate, and imprecise movements of the articulators (Dromey, Kumar, Lang, & Lozano, 2000). In addition, individuals with Parkinson's disease frequently have reduced facial animation and limited mobility of their oral musculature (Farrell, Theodoros, Ward, Hall, & Silburn, 2005).

Speech Intelligibility. While studying the acoustic and perceptual consequences of articulatory rate change in the speech of patients with Parkinson's disease, McRae, Tjaden, and Schoonings (2002) noted that previous studies had shown the size of the vowel acoustic working space to be an important component in estimations of global speech intelligibility in individuals with amyotrophic lateral sclerosis. They also reported that larger vowel space affected the acoustic-perceptual distinctiveness of speech sounds and positively impacted listeners' perceptual judgments of intelligibility. Furthermore, McRae et al. found that speakers with Parkinson's disease tend to have a decreased vowel space area when compared to age and gender matched controls. This particular measure reflects a reduction in tongue excursions during speech, which may be an important factor in the overall intelligibility of these speakers. A study performed by Bradlow, Torretta, and Pisoni (1996) investigated the various characteristics of individuals with normal speech to determine which factors correlated with their level of perceived intelligibility. They found that a reduction in the speaker's vowel space area resulted in a concomitant decrease in the overall speech intelligibility score. These findings were consistent with the research of Tjaden and Wilding (2004), which indicated that healthy speakers with larger vowel space areas were judged to be more intelligible than healthy speakers with smaller vowel space areas. They pointed out that dysarthric individuals tend to have smaller displacements of the articulators during speech, and that this causes the acoustic working space, and along with it the vowel space area, to be reduced. In their study, Tjaden and Wilding noted that vowel space area for a group of patients with Parkinson's disease was not statistically different across the conditions of reading out loud at slow, habitual, and fast paces. However, the vowel space area of several of the speakers with Parkinson's was greatest in the slow reading condition. These findings suggest that decreasing speaking rate may be an effective tool for optimizing the vowel space area of patients with Parkinson's disease to help improve the intelligibility of their speech.

Treatment of Parkinson's Disease

Medication. The neurologist's goal in prescribing medications for the management of Parkinson's is to effectively control the symptoms of the disease while simultaneously minimizing the side effects of the drug. Although Parkinson's disease results from a dopamine deficiency in the brain, dopamine is not a useful drug treatment because it cannot cross the blood-brain barrier. As a result, its precursor *levodopa* has been used because it is able to penetrate this barrier (Meara & Koller, 2000). Levodopa has been shown to effectively treat parkinsonian symptoms such as bradykinesia and rigidity. A study performed by De Letter et al. (2005) demonstrated that individuals with Parkinson's disease who were taking levodopa were significantly more intelligible on a single word level than they were without taking medication. Common side effects of levodopa include nausea and vomiting (Meara & Koller, 2000). When it was first introduced in 1968, levodopa caused considerable optimism in the management of Parkinson's disease (Wonodi, Hong, Avila, & Thaker, 2005), thus doing away with virtually all surgical treatments that were being used (Fields & Tröster, 2000). Unfortunately, it was subsequently discovered that individuals with Parkinson's disease who had been on levodopa for an extended period of time exhibited problems such as drug-induced dystonia and dyskinesia (De Letter et al., 2005; Metman & Mouradian, 1999). Many patients also experience *on-off effects*, or unpredictable time periods when the motor benefits of levodopa are stable and then suddenly deteriorate (Uitti, 2000). Pinter et al. (1999) stated that:

> Although parkinsonian signs can be effectively controlled in the first years of treatment by oral administration of antiparkinsonian drugs, progression of disease entails long-term problems in the form of unpredictable motor fluctuations, sometimes accompanied by disabling peak dose and diphasic dyskinesia. (p. 694)

Surgery. In addition to medication, surgical intervention is another treatment method that Parkinson's patients may consider to help relieve symptoms associated with their disease. Surgical procedures are only appropriate for individuals in the more advanced stages of the disease who are no longer benefiting from typical forms of medical therapy (Blumin, Pcolinsky, & Atkins, 2004). In general, patients should only consider surgical management of Parkinson's disease after they have tried several different types of medication, with all of them being either non-beneficial or intolerable for the patient (Playfer & Hindle, 2001). Several different surgical procedures have been attempted to alleviate the symptoms of Parkinson's disease, although none of them are done specifically with the intent of improving speech production.

Thalamotomy and Pallidotomy. Thalamotomy is a procedure that involves creating a lesion in the ventrolateral nucleus of the thalamus to relieve tremor. A similar procedure that can be done to reduce tremor, akinesia, or postural instability is a pallidotomy, in which a lesion is made in the posteroventral portion of the globus pallidus (Duffy, 2005). Prior to the 1960s, these surgeries were performed regularly to treat symptoms of Parkinson's disease, but the frequency of these operations decreased dramatically when levodopa became widely available (Tröster, 2000). However, renewed interest in these surgical interventions was sparked in the past decade as it became ever clearer that levodopa, when used for an extended period of time, caused problems of its own (Parkin et al., 2002).

As is the case for many surgeries, there are serious risks associated with these procedures. Recent research suggests that thalamotomy and pallidotomy do not always result in improved motor function (Maruska, Smit, Koller, & Garcia, 2000). Furthermore, there has been very little evidence of speech improvements following these surgeries. Farrell et al. (2005) found that in general, thalamotomy and pallidotomy did not lead to significant positive changes in speech. However, other studies have shown that when pallidotomy is performed bilaterally, any dysarthria that the patient exhibited prior to surgery may worsen after undergoing this procedure. Furthermore, it may result in hypophonia, drooling, and dysphagia (Duffy, 2005). Bilateral lesions made in thalamotomy procedures have been known to cause persistent severe dysarthria and cognitive deficits (Parkin et al., 2002; Shannon, 2000).

Deep Brain Stimulation (DBS). In January of 2002, the Food and Drug Administration approved deep brain stimulation DBS (Cleveland Clinic, 2003, para. 17), and in recent years it has become an increasingly promising treatment method for regulating the symptoms displayed by Parkinson's patients. Surgery consists of the implantation of a thin, insulated lead with four electrodes at the tip into a particular area of the brain (Mayo Foundation for Medical Education and Research, 2006, para. 2). The electrodes emit electrical pulses that inhibit the abnormal brain signals originating from the target area that cause the symptoms of Parkinson's disease (Benabid et al., 1998; Cleveland Clinic, 2003, para. 3). A local anesthetic is applied to the patient's scalp prior to surgery. To ensure that the electrodes are placed in the desired anatomic location, the neurosurgeon uses magnetic resonance imaging to map the brain. Furthermore, the patient is awake during the procedure to participate in trial stimulation to allow documentation of changes in side effects, such as movements of the upper and lower extremities, speech changes, and eye deviation, at various voltages (Machado et al., 2006). Following electrode implantation, a general anesthesia is administered to the patient in preparation for the implantation of the wire lead and pulse generator (Mayo Foundation, 2006, para. 3). The wire lead connects the electrodes in the brain to the pulse generator, which is surgically inserted under the clavicle (Maruska et al., 2000).

A few weeks after surgery, the stimulators are turned on for the first time, and the generator output is adjusted with an external system to achieve optimal programming (Cleveland Clinic, 2003, para. 9). This can be done by modifying the polarity, amplitude, pulse width, and frequency of the pulse generator output (Törnqvist et al., 2004). Patients can also control the stimulation by turning it on or off with a handheld magnet (Shannon, 2000).

Individuals with Parkinson's disease who are considering this surgery should be aware of its potential side effects. The Cleveland Clinic (2003, para. 12) reported that during DBS, "There is approximately a two to three percent chance of brain hemorrhage that may be of no significance, or may cause paralysis, stroke, speech impairment or other major problems." According to the Mayo Foundation for Medical Research and Education (2006), side effects of implantation are usually minimal but may include temporary tingling in the limbs, slight paralysis, slurred speech, or loss of balance. Despite this, DBS may be preferred over tissue ablation procedures because the negative effects of DBS can be reversed by modifying the parameters of the stimulator or by removing the hardware (Playfer & Hindle, 2001), whereas problems that result from lesions made in thalamotomy and pallidotomy are permanent.

In addition, some complications may result from the actual hardware that is implanted into the brain. Although it is uncommon, some patients may get an infection. If this occurs, it can usually be resolved by removing the electrodes. Others may experience difficulties such as electrode migration or battery depletion. Battery life will vary depending on use of the deep brain stimulator; reports indicate that a battery can last anywhere from two to five years before it needs to be replaced (Mayo Foundation, 2006, para. 6; Shannon, 2000). Replacement of the battery also requires replacement of the pulse generator, which can be done in a quick outpatient procedure (Mayo Foundation, 2006, para. 6).

Documented Effects of Deep Brain Stimulation (DBS)

Motor Characteristics. Despite the potential for occasional surgical complications, current research suggests that DBS of the subthalamic nucleus has become the preferred treatment method for patients with more advanced Parkinson's disease because it improves all of the key symptoms of the disease better than those observed from stimulation of the globus pallidus (Wang, Metman, Bakay, Arzbaecher, & Bernard, 2003). Furthermore, patients can significantly decrease the dosage levels of levodopa they need to control their symptoms when it is used in conjunction with stimulation of the subthalamic nucleus (Playfer & Hindle, 2001).

Speech Characteristics. Research into the effects of DBS on speech has yielded mixed results. Some studies have shown that DBS procedures in Parkinson's disease lead to improvements in general motor function that are far more positive than those demonstrated in speech. When studying the effects of neurosurgical management of Parkinson's disease on speech characteristics and oromotor function, Farrell et al. (2005) found that the Parkinson's group that had surgery (thalamotomy, pallidotomy, or DBS) displayed a marked reduction in Hoehn and Yahr staging of Parkinson's disease scores when compared with the non-surgery Parkinson's group, but there were no significant changes in the participants' speech. Other reports revealed that speech can be negatively affected with surgical intervention. Gentil, Pinto, Pollak, and Benabid (2003) suggested that "speech may be worsened with STN stimulation when using excessively high or too low stimulation parameters and in case of incorrect location of deep brain electrodes in the STN" (p. 194). Other reports concluded that, in addition to the frequency setting, the amplitude setting was an important factor in the level of intelligibility of a patient receiving stimulation of the subthalamic nucleus, with a higher amplitude setting resulting in a decrease in speech intelligibility (Törnqvist et al., 2004). Gentil et al. (2003) demonstrated that the speech of subjects who had mild or moderate dysarthria without stimulation was negatively affected by stimulation of the ventral intermediate nucleus of the thalamus. However, all participants in their study who received stimulation of the subthalamic nucleus demonstrated marked improvements in speech. Wang et al. (2003) showed that bilateral stimulation in the subthalamic nucleus had some positive effects on speech when comparing stimulator-on and stimulator-off conditions. However, they found no changes in speech with unilateral stimulation. Gentil, Garcia-Ruiz, Pollak, and Benabid (2000) found that bilateral stimulation of the subthalamic nucleus improved the strength, precision, and movement of the articulators in speakers with Parkinson's disease.

Conclusion

Although there is no "one size fits all" treatment for patients with Parkinson's disease, research indicates that DBS of the subthalamic nucleus can be beneficial for many individuals. This treatment method generally improves motor functioning, but further research needs to be done to determine specific characteristics of the speech of patients with Parkinson's disease who have undergone DBS. The purpose of the current study was to further investigate the effects that DBS has on the speech of Parkinson's patients. This was done by obtaining and analyzing speech acoustic measures including vowel space area, formant slopes, long term average spectrum, stop closure duration, voice onset time, diadochokinetic rate, and spirantization. Vowel space area is relevant to patients with Parkinson's disease because it is a reflection of the extent of tongue movement during speech, and studies have linked this particular measure to ratings of intelligibility and overall speech quality. Similarly, formant slopes provide information regarding rate and extent of tongue movements in the production of diphthongs. Long term average spectrum, which indirectly reflects voice quality, and verbal fluency, stop closure duration, voice onset time, diadochokinetic rate (regular and distracted), and spirantization, which reflect coordination of articulators, were studied because of previous reports (Dromey, 2003; Duffy, 2005; Weismer, 1984) that these particular measures are often abnormal in individuals with Parkinson's disease.

Method

The current study was part of a larger research effort that will continue over a period of several years. In addition to those discussed below, several other measures were collected that will be pertinent for future research projects. They will not be included in the present report.

Participants

Participants included 6 patients between the ages of 48 - 79 years, with a mean of 59.8 years (see Table 1). All patients were diagnosed by a neurologist as having mild to moderate idiopathic Parkinson’s disease, with the time since diagnosis ranging from 4 to 24 years and a mean of 13.8 years. All participants were candidates for surgical treatment of Parkinson’s disease at the University of Utah Medical Center, specifically DBS of the subthalamic nucleus, to alleviate symptoms associated with the disorder. Participants were selected for the current study based on reports of speech deterioration accompanying stimulation. All participants volunteered to be in the present study and signed an informed consent document.

Speaking Tasks and Speech Sample

Participants read the sentence “The boot on top is packed to keep” to elicit productions of the corner vowels /i/, /ɑ/, /u/, and /æ/ in a consonant-vowel-consonant context. This sentence was selected because it had a stress pattern that mimics that of natural speech, and each word containing a vowel of interest received stress. The sentence “The boy gave a shout at the sight of the cake” was also read to elicit the diphthongs /ɔɪ/, /aʊ/, /aɪ/, and /eɪ/. Each participant repeated both sentences five times and then read the first six sentences of the Rainbow Passage (Fairbanks, 1960). A

Table 1

Demographic Data from Participants with Parkinson's Disease

Participant	Gender	Age	Years Post Diagnosis	Medications
F1	F	79	24	Carbidopa/Levadopa Mirapex
M4	M	56	4	Carbidopa/Levadopa
M5	M	50	18	Carbidopa/Levadopa
M8	M	54	15	Carbidopa/Levadopa
M9	M	72	12	Carbidopa/Levadopa
M10	M	48	10	Carbidopa/Levadopa Mirapex

spontaneous speech sample was obtained by having participants describe the Cookie Theft picture from the third edition of the Boston Diagnostic Aphasia Examination (Goodglass, Kaplan, & Barresi, 2000) for a one minute period. Diadochokinetic rate (DDK) was recorded with each participant only speaking, and then again while the participant was distracted by simultaneously speaking and twisting a nut around a long bolt. The regular and distracted diadochokinetic rate tasks were separated by a one minute verbal fluency task in which participants were instructed to name all of the words they could think of that started with the letter *r*, *w*, or *p*. The initial letter of the word was selected at random by the clinician, and the letter selected for each participant was different in the on and off conditions. Finally, participants were instructed to take a deep breath and then sustain /ɑ/ for as long as possible.

Instrumentation

During each of these tasks, the acoustic signal was recorded into a Dell laptop computer via a headset microphone (AKG C-420) with a mouth-to-microphone distance of approximately 5 cm. A Tascam US-122 USB interface was used to digitize the acoustic signal from the microphone. A sound level meter (Extech 407736) was used to calibrate the microphone signal intensity.

All participants performed each of the tasks at least six months after surgery under the following conditions to allow for comparisons: optimal medication and the stimulator *on*, optimal medication and the stimulator *off*. A minimum recovery period of six months was used because the stimulation parameters of the pulse generator have been optimally programmed by that time, and thus speech quality and limb function are generally stable. After recording participants in the *on* condition, the stimulator was turned off; subsequent recordings in the *off* condition took place one hour later to ensure that the effects of stimulation would be essentially absent.

Data Analysis

From the digital recordings of the sentence *The boot on top is packed to keep*, the first and second formant frequencies of the corner vowels were measured using PRAAT 4.5.18. (Boersma & Weenink, 2007).

After the raw formant data were computed with Praat, vowel space area was calculated using MATLAB 7.1 (The Mathworks, 2005). This was done by collapsing the five tokens of the corner vowels /i/, /ɑ/, /u/, and /æ/, which were extracted from the recordings of the sentence reading task (*The boot on top is packed to keep*), to obtain averages of the first two formant frequencies for each vowel. The averages were then plotted in MATLAB to create a vowel quadrilateral. The quadrangle area was calculated using the MATLAB polygon area function to determine total vowel space area for each participant during both the optimal medication and stimulator on and optimal medication and stimulator off conditions.

To determine the effect of DBS on the rate and extent of tongue movement in the productions of diphthongs, the diphthongs /ɔɪ/, /ɑʊ/, /ɑɪ/, and /eɪ/ were extracted from five repetitions of the sentence *The boy gave a shout at the sight of the cake* using Praat. The slope of the first two formants of the diphthongs were computed in each condition, after which the values across the 5 repetitions were averaged together to obtain a mean slope for F1 and F2 for each diphthong for each participant.

To obtain measures of verbal fluency, a count was taken of the number of words each participant was able to produce in a 30 second period in each condition. All non-words that were produced were not included in the total.

The acoustic analysis used to assess diadochokinetic (DDK) rate was consistent with the protocol of Tjaden and Watling (2003), in which DDK rate was defined as “the number of syllables, including partial syllables, produced during [a] 2-second analysis interval” (p. 245). The analysis window started at the onset of the stop release for the second repetition of /pə/, /tə/, or /kə/ in the alternating motion rates (AMR) task and at the onset of the stop release of the second repetition of /pətəkə/ in the sequential motion rate (SMR) task. The end of the analysis window was two seconds after the onset, and any partial syllables that were produced during the offset were included in the syllable count for DDK. If participants were directed to repeat an attempt at producing a syllable train, the second set of repetitions was used for analysis. The same is true for all measures that were calculated using the syllable repetitions.

Using the TF32 program (Milenkovic, 2000) the long term average spectrum (LTAS) was calculated for the picture description task and the Rainbow Passage that was read by each participant. Long term average spectrum was also performed on a sustained /ɑ/ vowel to determine if the results were consistent with the findings of the connected speech tasks. This measure was of particular interest because Dromey (2003) has shown that statistical measures of the LTAS shape, referred to as *spectral moments*, of the long term average spectrum are sensitive to changes in voice quality associated with speakers with hypokinetic dysarthria. The first two spectral moments (mean and standard deviation) of the LTAS were used to indirectly assess the voice quality of participants in each condition.

Stop closure duration and voice onset time (VOT) were calculated using TF32 to segment the desired portions of the syllable repetitions from the AMR task. Voice onset time was defined as the time from the stop release to the end of the frication and aspiration of the stop. Repetitions two through six of the stop consonants /p/, /t/, and /k/ were averaged together to obtain a mean stop closure duration and VOT for each participant in each test condition. Both the spectrographic display and the waveform were used to determine the boundaries of the stop closure.

Spirantization during the AMR task was assessed by computing an RMS voltage ratio using the RMS trace in TF32. This was done by selecting a 30 ms segment in the middle of the /ə/ vowel, as well as a 30 ms segment in the middle of the following stop closure, and recording the RMS mean for each. The procedure was repeated for repetitions 1-10 of /pə/, /tə/, and /kə/ (including partial syllables) produced by each participant with and without stimulation. Finally, an average vowel RMS and stop closure RMS were determined and a ratio was calculated.

Results

Due to the small number of participants in the current study, it is difficult to make generalizations to a larger population. Because of this, participants were viewed as six separate case studies. Descriptive statistics were used to provide measures of vowel space area, slope of formant frequencies of diphthongs, long term average spectrum, verbal fluency, DDK rate, voice onset time, stop closure duration, and spirantization in the two test conditions.

Vowel Space Area

The average first and second formant frequencies of the corner vowels /u/, /ɑ/, /æ/, and /i/ for each participant with and without stimulation are presented in Table 2. These averages were used in a MATLAB program to calculate the vowel space area with the stimulator on and off for each participant. Figure 1 provides a side-by-side comparison of vowel quadrilaterals with and without stimulation for each participant. Due to frequency jumping in Praat, accurate measures could not be obtained for participant M9 with stimulation. Therefore, a vowel quadrilateral was not made for that participant in the *on* condition. According to the calculations of vowel space area, three out of five participants had a larger vowel space area in the *off* condition when compared to the *on* condition.

Formant Slopes

The slope values of the first (F1) and second (F2) formants for the diphthongs /ɔɪ/, /ɑʊ/, /ɑɪ/, and /eɪ/ are shown in Table 3. When comparing F1 slope across stimulation conditions, one participant had increase in slope for three of the four diphthongs with stimulation on, and three participants showed a slope increase for two out of four

Table 2

Average F1 and F2 for Corner Vowels /u/, /ɑ/, /æ/, /i/ with Stimulation On and Stimulation Off

		Stimulation On		Stimulation Off	
Vowel	Participant	F1	F2	F1	F2
/u/	F1	360	1700	394	1775
	M4	378	1358	359	1266
	M5	393	1434	396	1487
	M8	356	1465	333	1434
	M9	348	1223	328	1121
	M10	335	1428	366	1472
/ɑ/	F1	589	1421	517	1428
	M4	734	1318	724	1323
	M5	622	1284	650	1389
	M8	640	1094	650	1057
	M9	653	1593	662	1186
	M10	611	1282	611	1323
/æ/	F1	564	1747	589	1818
	M4	720	1618	731	1625
	M5	654	1645	615	1735
	M8	676	1514	700	1487
	M9	584	1597	664	1566
	M10	609	1673	622	1636
/i/	F1	353	2369	365	2473
	M4	284	2366	280	2459
	M5	271	2167	309	2086
	M8	367	2137	257	2114
	M9	328	2063	288	2119
	M10	292	2230	310	2223

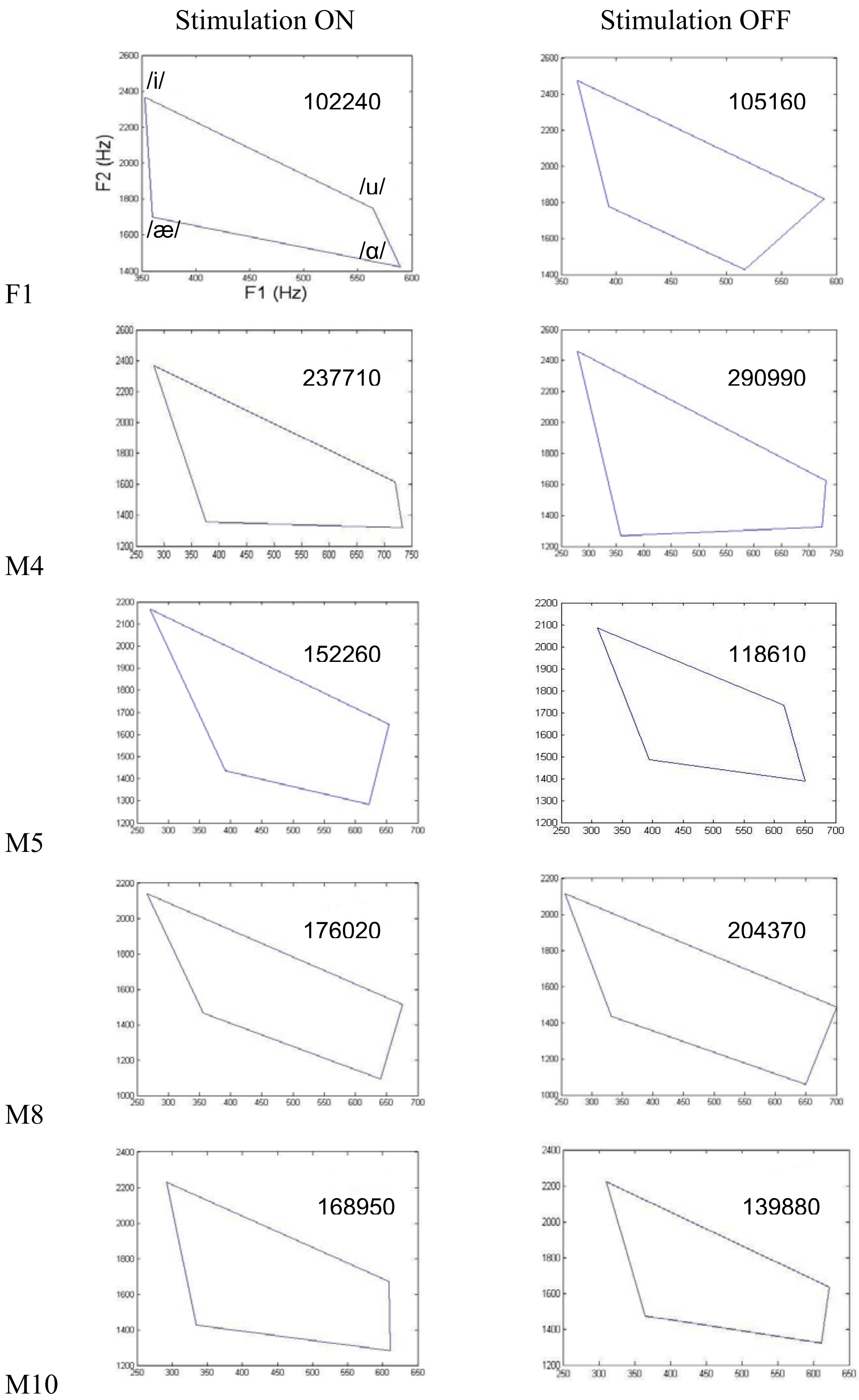

Figure 1. Plots of F1 versus F2 expressed in Hz^2 for all participants except M9 (ON formant data unavailable).

Table 3

Average F1 and F2 Slope for Diphthongs /ɔɪ/, /aʊ/, /aɪ/, and /eɪ/ with Stim On and Off

		Stimulation On		Stimulation Off	
Participant	Diphthong	F1	F2	F1	F2
F1	/ɔɪ/	-0.74	11.07	-0.60	9.26
	/ɑʊ/	-0.94	-0.85	-0.55	-0.34
	/ɑɪ/	-0.15	2.98	-0.86	2.61
	/eɪ/	-2.31	4.81	-2.64	2.69
M4	/ɔɪ/	-0.24	6.45	-0.24	7.82
	/ɑʊ/	0.32	-3.87	0.02	-2.79
	/ɑɪ/	-0.78	3.35	-0.97	2.59
	/eɪ/	-0.87	0.95	-0.68	1.54
M5	/ɔɪ/	-0.68	9.79	-0.08	8.62
	/ɑʊ/	0.37	-3.19	0.21	-2.15
	/ɑɪ/	-1.53	3.22	-1.57	3.61
	/eɪ/	-0.45	2.02	-0.10	2.63
M8	/ɔɪ/	-0.88	8.46	-0.10	8.58
	/ɑʊ/	0.57	-1.86	0.69	-2.43
	/ɑɪ/	-0.60	2.46	-1.23	2.54
	/eɪ/	-0.84	1.44	-0.49	0.94
M9	/ɔɪ/	-0.80	9.47	-1.21	9.64
	/ɑʊ/	-0.32	-2.16	0.29	-1.92
	/ɑɪ/	-0.62	2.62	-0.86	1.50
	/eɪ/	-0.69	1.72	-1.18	2.01
M10	/ɔɪ/	-1.00	11.50	-0.79	10.86
	/ɑʊ/	0.23	-2.65	0.49	-3.12
	/ɑɪ/	-0.49	4.44	-0.49	2.85
	/eɪ/	-0.83	1.17	-0.83	-0.06

diphthongs with stimulation on. The two remaining participants appeared to perform more poorly with stimulation, as they only demonstrated a greater F1 slopes in the *on* condition for one diphthong. Thus, with 24 total diphthong productions (four diphthongs × six participants), stimulation resulted in an increase in F1 slopes for 11 of the tokens, no change in the slopes of three diphthongs, and a decrease in slopes for 10 diphthongs.

The results for F2 slope were also quite variable. Stimulation resulted in an increase in F2 slope for all four diphthongs for one participant and three out of four diphthongs for another. Three participants were equally divided across conditions, with an increase in slope for two of the diphthongs with stimulation on and an increase in slope for the other two diphthongs with stimulation off. The remaining participant only exhibited in greater F2 slope for one diphthong in the stimulation on condition. Therefore, 14 of the 24 diphthongs produced had higher F2 slopes with stimulation, while the F2 slopes of 10 diphthongs were greater without stimulation.

Verbal Fluency

Two counts of verbal fluency were deemed necessary because some participants used proper names whereas others did not. Participants were simply directed to name as many words as possible that started with a particular letter, and it was unclear as to whether or not those that did not use proper names refrained from doing so because they assumed such words were unacceptable. Therefore, the first count recorded was strict and did not include proper names, and the second was a lenient count in which proper names were added into the total. The results of both counts are shown in Table 4. Despite this differentiation, the data are consistent in both counts of verbal fluency, indicating that four of the six participants were able to produce more words in the *off* condition than in the *on* condition.

Table 4

Lenient (Proper Names Included) and Strict (Proper Names Excluded) Counts of Verbal Fluency With and Without Stimulation

Participant	Count	Stim On	Letter	Stim Off	Letter
F1	strict	5	r	9	p
	lenient	5	r	9	p
M4	strict	9	p	10	r
	lenient	9	p	12	r
M5	strict	1	w	4	p
	lenient	4	w	5	p
M8	strict	9	r	16	p
	lenient	11	r	22	p
M9	strict	8	r	6	p
	lenient	8	r	7	p
M10	strict	8	w	4	r
	lenient	9	w	6	r

Diadochokinetic Rate

Regular and distracted DDK rates with and without stimulation and distraction are shown in Table 5. Four different comparisons were made for the AMR task. To determine the effects of stimulation on DDK rate, the following two conditions were compared: on regular vs. off regular; on distracted vs. off distracted. To determine the effects of distraction on DDK rate, the following conditions were compared: on regular vs. on distracted; off regular vs. off distracted. Comparisons were made across syllables, resulting in 18 different DDK rates (three syllables × six participants).

An evaluation of regular DDK to compare on and off differences revealed that six rates were higher with stimulation, eight rates were the same in both conditions, and four rates were higher with no stimulation. Comparison of distracted DDK across stimulation conditions showed that only two rates were higher with stimulation, seven rates were the same with and without stimulation, and nine rates were higher with stimulation off. When comparing regular and distracted DDK rates across all participants in the *on* condition, ten rates were found to be highest with no distraction, seven rates were the same regardless of distraction, and one rate was better with distraction. Comparisons of regular and distracted DDK rate with stimulation off revealed that six rates were higher with no distraction, eight rates were the same regardless of distraction, and four rates were higher with distraction.

In terms of participant performance on particular syllables, DDK rate was typically lowest for the /kə/ syllable across all conditions. Although DDK rate for /kə/ was often the same as that of other syllables, it was never higher than the other two

Table 5

Diadochokinetic Rate (syllables/s) of Participants With and Without Stimulation

		Stimulation On		Stimulation Off	
Participant	Syllable	Regular	Distracted	Regular	Distracted
F1	/pə/	7.5	6	6	6
	/tə/	6	5.5	6	6
	/kə/	6	5.5	5.5	6
	/pətəkə/	1.5	1.5	1.5	2.5
M4	/pə/	5	5	5.5	5
	/tə/	5	5	4.5	5
	/kə/	5	3	4.5	4.5
	/pətəkə/	2	2	2	2
M5	/pə/	6.5	5.5	6	6
	/tə/	6	5	7	6
	/kə/	5.5	5	6.5	5.5
	/pətəkə/	1	2.5	2	2
M8	/pə/	7.5	6.5	6.5	5.5
	/tə/	6.5	6.5	6.5	4.5
	/kə/	4	5	4.5	5.5
	/pətəkə/	2	2	2	2
M9	/pə/	5.5	5	5.5	5.5
	/tə/	5	5	5	5
	/kə/	4.5	4.5	4.5	5
	/pətəkə/	-	-	-	-
M10	/pə/	7.5	7	7.5	7
	/tə/	7	7	7	7
	/kə/	6.5	6.5	6.5	6.5
	/pətəkə/	-	-	-	-

Note. - = data were not collected for these participants syllables for any participants. In contrast, the DDK rate for the /pə/ syllable was either the same or better than the /tə/ and /kə/ syllables for all participants.

Diadochokinetic rate was only calculated for four of the six participants for the SMR task, as this information was not obtained for two individuals. The four comparisons made for the AMR task were also used to assess SMRs. All comparisons revealed that rates were typically the same in all conditions except one. In the *on* distracted vs. *off* distracted comparison showed that one rate was higher with stimulation, two rates were the same, and one rate was higher with no stimulation.

Long Term Average Spectrum

As shown in Table 6, the spectral mean in the LTAS was higher in the absence of stimulation for four of the six participants while reading the Rainbow Passage (Fairbanks, 1960). Table 7 shows that, in the picture description task, four out of five participants also demonstrated a higher spectral mean with the stimulators off. The picture description was not recorded in the *on* condition for participant M4; therefore, this person was excluded from the analysis. Finally, Table 8 shows the spectral mean and SD for the LTAS of a sustained /ɑ/. These results were not consistent with those of the reading and picture description tasks in that four participants had a higher spectral mean in the *on* condition.

Voice Onset Time

Table 9 shows the average voice onset time of participants during repetitions two through six of the AMR task. The results indicate that one of six participants had a longer average VOT for all three stop consonants (/p/, /t/, /k/) with stimulation on. On the other hand, three of the six participants demonstrated a shorter average VOT for two out of

Table 6

Spectral Moments (M and SD) of the Long Term Average Spectrum While Reading the Rainbow Passage (Fairbanks, 1960) With and Without Stimulation

	Stimulation On		Stimulation Off	
Participant	*M* (kHz)	*SD*	*M* (kHz)	*SD*
F1	6.55	4.80	7.01	4.56
M4	5.07	5.20	4.23	4.61
M5	7.72	5.29	7.34	5.30
M8	4.19	4.77	4.71	4.60
M9	4.03	5.56	6.46	5.93
M10	7.49	3.29	8.18	2.78

Table 7

Spectral Moments (M and SD) of the Long Term Average Spectrum of the Picture Description Task With and Without Stimulation

	Stimulation On		Stimulation Off	
Participant	*M* (kHz)	*SD*	*M* (kHz)	*SD*
F1	7.68	4.42	8.00	4.40
M4	-	-	5.00	4.85
M5	8.76	4.96	7.84	5.14
M8	4.02	3.95	4.08	4.81
M9	3.65	5.10	7.00	5.17
M10	7.93	2.89	8.64	2.55

Note. - = data were not collected for this participant.

Table 8

Spectral Moments (M and SD) of the Long Term Average Spectrum While Sustaining /a/ With and Without Stimulation

	Stimulation On		Stimulation Off	
Participant	*M* (kHz)	*SD*	*M* (kHz)	*SD*
F1	3.85	3.25	3.54	4.38
M4	2.39	3.50	3.29	3.86
M5	2.20	2.80	1.56	2.74
M8	2.77	4.14	1.76	3.02
M9	8.31	5.34	8.49	4.90
M10	6.89	6.03	3.67	5.01

Table 9

Mean and SD of Voice Onset Time (ms) of Stop Consonants /p/, /t/, and /k/ for Repetitions 2-6 of the Alternating Motion Rate Task

		Stimulation On		Stimulation Off	
Participant	Phoneme	*M*	*SD*	*M*	*SD*
F1	/p/	29.60	10.43	31.07	5.24
	/t/	36.66	3.74	40.44	3.19
	/k/	45.09	5.53	56.05	23.85
M4	/p/	28.49	4.55	26.84	4.48
	/t/	32.41	2.78	34.35	13.32
	/k/	58.56	7.42	75.87	23.45
M5	/p/	44.86	12.86	41.91	13.65
	/t/	32.81	4.89	29.17	5.84
	/k/	-	-	-	-
M8	/p/	20.77	5.44	18.43	5.79
	/t/	38.37	7.71	42.39	7.14
	/k/	52.37	2.26	51.82	18.16
M9	/p/	-	-	26.35	6.31
	/t/	29.17	8.17	36.30	7.23
	/k/	-	-	58.22	12.53
M10	/p/	19.08	1.39	27.49	4.58
	/t/	34.46	5.06	32.31	3.25
	/k/	42.10	9.18	39.14	3.80

Note. - = measure could not be obtained due to continuous voicing between consonants.

three stop consonants with stimulation off. One participant, for whom average VOT could only be compared for two consonants, demonstrated a longer average VOT for one consonant with stimulation on and then a shorter average VOT for the other consonant with stimulation off.

Stop Gap Duration

The results for average stop gap duration for repetitions 2-6 of the AMR task are shown in Table 10. Because of continuous voicing through several stop gaps in several repetitions of two participants, their results were not conducive to comparisons. Of the remaining four participants, one exhibited a longer average stop closure for all three consonants with stimulation on, and two other individuals demonstrated a longer average stop gap across two of the three consonants with stimulation. Only one participant had a longer average stop closure for a majority of consonants without stimulation. There did not appear to be a relationship between stop gap duration and initial phoneme.

Spirantization

Table 11 shows the ratios of vowel RMS to stop closure RMS for repetitions 1-10 of the AMR tasks. Three of the six participants demonstrated a higher RMS voltage ratio for all three syllables with stimulation on, and one participant had a higher RMS voltage ratio for only two of the syllables with stimulation. Two participants performed better with stimulation off, one showing a higher ratio for two syllables and the other exhibiting a much higher ratio for all three syllables.

Table 10

Mean and SD of Stop Closure (ms) of Stop Consonants /p/, /t/, and /k/ for Repetitions 2-6 of the Alternating Motion Rate Task

		Stimulation On		Stimulation Off	
Participant	Phoneme	*M*	*SD*	*M*	*SD*
F1	/p/	63.95	16.89	78.38	10.17
	/t/	57.32	10.94	53.61	8.82
	/k/	47.80	9.24	38.57	12.77
M4	/p/	107.47	5.70	101.88	9.01
	/t/	100.29	6.28	91.06	13.80
	/k/	77.84	6.97	89.68	20.59
M5	/p/	45.72	11.59	47.98	14.07
	/t/	46.42	8.92	41.30	11.10
	/k/	-	-	-	-
M8	/p/	76.10	17.56	66.02	16.32
	/t/	65.99	8.36	39.65	10.05
	/k/	151.87	105.52	50.12	16.59
M9	/p/	-	-	26.35	6.31
	/t/	59.15	15.84	66.96	14.49
	/k/	-	-	50.98	9.89
M10	/p/	54.93	16.88	52.60	12.10
	/t/	31.28	10.72	43.22	4.01
	/k/	30.92	6.99	52.16	3.88

Note. - = measure could not be obtained due to continuous voicing between consonants.

Table 11

Ratios of Mean Vowel RMS to Mean Stop Closure RMS to Indicate Spirantization Energy In Repetitions 1-10 of Syllables /pə/, /tə/, and /kə/

Participant	Syllable	Ratio Stim On	Ratio Stim Off
F1	/pə/	3.43:1	1.86:1
	/tə/	9.60:1	5.50:1
	/kə/	4.30:1	3.00:1
M4	/pə/	13.67:1	12.50:1
	/tə/	16.67:1	11.50:1
	/kə/	10.50:1	6.25:1
M5	/pə/	2.93:1	3.69:1
	/tə/	9.25:1	9.15:1
	/kə/	5.00:1	3.91:1
M8	/pə/	31.00:1	18.00:1
	/tə/	16.00:1	19.50:1
	/kə/	12.50:1	13.50:1
M9	/pə/	2.56:1	22.75:1
	/tə/	3.59:1	12.20:1
	/kə/	1.77:1	11.50:1
M10	/pə/	7.89:1	7.60:1
	/tə/	7.43:1	6.00:1
	/kə/	6.86:1	5.20:1

Discussion

The purpose of the current study was to further investigate the effect that DBS has on the speech of participants with Parkinson's disease. This involved assessment of several speech acoustic measures.

Vowel Space Area

Tjaden and Wilding (2004) reported that reduced vowel space area is characteristic of individuals with Parkinson's disease as a result of smaller displacements of the articulators during speech. Poluha, Teulings, and Brookshire (1998), who studied changes in vowel space area across the levodopa cycle, hypothesized that vowel space area would increase as levodopa effectively reduced rigidity and bradykinesia associated with Parkinson's disease; however, they found no significant changes in vowel space area across the medication cycle. Because the speakers in the present study were selected based on reports of worsened dysarthria with stimulation, it was hypothesized that stimulation would result in smaller vowel space area. This was found to be true for a large majority of the participants.

Formant Slopes

Forrest, Weismer, and Turner (1989) found that the formant transitions of patients with PD were smaller than those of normal geriatrics. Poluha et al. (1998) hypothesized that a reduction in rigidity and bradykinesia from PD patients' use of levodopa would permit faster articulatory changes and thus result in a greater F2 slope. Assuming that stimulation of the subthalamic nucleus was an effective means of decreasing the rigidity and bradykinesia of PD participants, the present study supported this notion, as the majority of diphthongs produced had greater F1 and F2 slopes with stimulation on.

It is of note that these findings do not coincide with the results of vowel space area. Although both measures reflect the extent and rate of tongue movement during speech, vowel space area is a measure of an individual's acoustic working space while formant slopes are an indication of transitions from the onset vowel to the offset vowel in a diphthong. Therefore, despite the decreases in total acoustic working space with stimulation, the formant transitions nonetheless increased under stimulation.

Verbal Fluency

Tröster, Wilkinson, Fields, Miyawaki, and Koller (1998) investigated the impact of chronic electrical stimulation to the left ventrointermediate (Vim) thalamic nucleus on semantic and episodic memory of patients with Parkinson's disease and found that, regardless of medication, stimulation of the Vim resulted in improvements of semantic verbal fluency but had a negative impact on ability to recall word lists. They therefore hypothesized that Vim stimulation might help with semantic memory but interfere with episodic memory. The results of the current study show that this may not necessarily be true for stimulation of the STN, as stimulation resulted in poorer performance with verbal fluency tasks for four out of six participants.

Diadochokinetic Rate

While studying the characteristics of DDK in Multiple Sclerosis (MS) and Parkinson's disease, Tjaden and Watling (2003) found that there was no difference between the PD group and healthy controls in the AMR task. Similarly, Ackermann, Hertrich, and Hehr (1995) characterized the syllable repetitions of PD subjects as having a fairly normal syllabic rate. Duffy (2005) stated that maximum rates for speech AMRs are generally five to seven repetitions per second, noting that rates for repetitions of /kə/ are typically slower than for those of /pə/ and /tə/. A majority of participants in the present study fell within this range across all conditions for the /pə/ and /tə/ syllables, with some displaying slightly higher rates for the /pə/ syllable and slightly lower rates for the /kə/ syllable. It has been suggested that PD patients essentially sacrifice the extent of movement of the articulators in order to produce syllables at a normal rate (Ackerman & Ziegler, 1991).

Tjaden and Watling (2003) also found that MS and PD groups performed significantly more slowly than controls in the SMR task. Although statistical analysis could not be performed in the current study, the SMRs were lower than even the lowest mean found across studies by Kent, Kent, and Rosenbek (1987).

Long Term Average Spectrum

With regards to LTAS, Dromey (2003) found that a low spectral mean and SD in PD generally suggests a weak upper harmonic structure, with most of the energy in the lower frequencies of the voice. In contrast, normal speakers had a higher SD, indicating a wider spread of energy across the spectrum. The present study showed that the spectral mean was higher for a majority of participants while reading the Rainbow Passage (Fairbanks, 1960) and for the picture description task in the *off* condition, but much lower for most participants while sustaining /ɑ/. It is also of note that the relationship between spectral mean and SD described by Dromey (2003), i.e. an increase in spectral mean is associated with a concomitant increase in SD, was not observed in the present study.

These findings suggest that stimulation resulted in an increase in hypophonia during the connected speech tasks rather than decreasing it. One possible explanation for the mismatch between the results of the reading and picture description tasks and the sustained vowel phonation task may be due to the fact that reading and describing a picture reflect more naturalistic speech, containing a combination of high and low frequency sounds (e.g. fricatives, affricates, stops, vowels, etc.), whereas vowel phonation consists primarily of the lower frequencies of the voice.

Voice Onset Time

Forrest et al. (1989) documented increased VOTs for Parkinson's patients when compared to normal geriatrics. Kent and Read (1992) reported norms for VOT, stating that the typical range for voiceless stops is anywhere from -20 ms to 100ms. After assessing the VOT of four patients pre- and post-pallidotomy, Ryalls, Hoffman-Ruddy, Vitek, and Owens (2001) found statistically significant decreases in the average and standard deviation VOT values for all stop consonants post-pallidotomy, noting that despite these decreases, all subjects were still within normal limits prior to surgery. In addition, a post-pallidotomy "place of articulation effect" (p.109), in which a longer VOT was associated with a more posterior place of articulation, was reported.

The findings of the current study support those of Ryalls et. all (2001), in that all participants had average VOTs that were within the range of normal performance according to the standards reported by Kent and Read (1992) in both stimulation conditions. In addition, the VOTs of all participants decreased for a majority of the total productions when the stimulators were on. A place of articulation effect was also noted for four out of six participants in the *on* condition and five out of six participants in the *off* condition. However, the current study did not find a pattern with SD values, which appeared to be quite variable among participants regardless of stimulation condition or initial phoneme of the syllable that was produced.

Stop Gap Duration

When comparing Parkinson's subjects to healthy geriatrics and young adults, Weismer (1984) reported that stop gap durations for fricatives, stops, and some clusters were "consistently and substantially shorter" (p. 122) for the Parkinson's group. Tjaden and Watling (2003) also found that stop gap durations were shorter for individuals with PD when compared to healthy controls, but the difference was not significant. Kent and Read (1992) reported that a stop gap is "typically between 50-150 ms of duration" (p. 110). In the current study, most participants' stop gap durations were within this range in both stimulation conditions, but there were several that fell short of 50 ms. The present study also showed that stop gap durations were longer for a majority of consonants in the *on* condition. This may reflect a decrease in stiffness and rigidity of the laryngeal musculature when stimulation is present, thus resulting in an improved ability to perform laryngeal devoicing more rapidly (Weismer, 1984).

Spirantization

Several studies have documented the presence of spirantization in the speech of individuals with PD (Kent et al., 1999; Weismer, 1984). In the present study, a lower RMS voltage ratio would suggest more severe spirantization. The higher ratio demonstrated by most participants for a majority of phonemes with stimulation on suggests improvements in articulatory closures.

Conclusion

In summary, those who participated in the present study were referred on the basis of worsened speech with DBS, yet the data indicated that this was not always the case. The results of the present study showed variability in the effect of DBS on participants' speech; some showed slight improvements with stimulation while others, particularly participant M9, performed markedly worse. The findings may have been impacted by the fact that the dysarthria of some participants was very mild to begin with.

One weakness in the current study was the small number of participants, thus making it impossible to perform statistical analysis to determine the significance of the findings and to allow for generalizations to be made. Therefore, it would be beneficial for a similar research project to be done with a larger sample. Also, a more comprehensive assessment of speech changes could be done by assessing the speech of participants before they undergo surgery in addition to obtaining post-surgery measurements with the stimulators on and off. Such information would be clinically relevant as it could help provide Parkinson’s patients who are considering DBS as a treatment option with a better understanding of the possible speech-associated benefits and risks of surgery. As it is possible that some individuals who opt for implantation will exhibit worsened speech with stimulation, it is important for neurology staff responsible for programming the stimulators after surgery to find the best possible balance between motor benefits and speech impairment to allow for the greatest quality of life.

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