VOICE ONSET TIME IN PARKINSON DISEASE

Emily Budkowski

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Committee:
Alexander Goberman, Advisor
Larry Small
Elizabeth Burroughs
ABSTRACT

Dr. Alexander Goberman, Advisor

Research examining Voice Onset Time (VOT) in individuals with Parkinson Disease (PD) has shown mixed results. Some research has shown longer VOTs, some have found shorter VOTs, while others have found a similar VOT between individuals with PD and controls. Previous research in non-neurologically impaired individuals has found that changes in speaking rate have an effect on VOT. Given that individuals with PD are known to exhibit speaking rate differences compared to controls, the current study examined VOT in individuals with PD based on two different measures: (1) the conventional VOT measure (VOT); and (2) VOT with the effect of rate removed (VOT Ratio). Results indicated a significant effect of place of articulation for voiceless sounds and a significant vowel height effect for the VOT ratio of voiceless sounds. Results indicated that there were no significant differences between the PD groups compared to controls for both VOT and VOT ratio. Within the PD group, levodopa appeared to have a greater effect on VOT than VOT ratio, meaning that the difference was actually more reflective of a medication-related rate change, rather than a pure VOT change. Overall, the current data support the usefulness of examining both VOT and VOT ratio with individuals with PD, as this method allows for dissociation between rate-related changes and true VOT-related changes.
ACKNOWLEDGMENTS

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INTRODUCTION AND REVIEW OF LITERATURE

Idiopathic Parkinson disease (PD) is a progressive neurodegenerative disease that affects over 1 million people in North America (Lang & Lozano, 1998a). Although a single causative factor is unknown, the most consistent risk factor is increasing age. One theory about the cause of PD maintains that a genetic predisposition in combination with certain environmental conditions may lead to the development of PD (Lang & Lozano, 1998a).

PD is characterized by the loss of dopaminergic neurons in the substantia nigra pars compacta, as well as other areas of the brain (Brodal, 1998; Lang & Lozano, 1998a). This loss results in dysfunction of the basal ganglia pathway, which is an essential part of the circuitry that mediates motoric and cognitive functions (Harel, Cannizzaro, Cohen, Reilly, & Snyder, 2004). As a result of the dopamine loss in the basal ganglia, there can be a number of motor symptoms such as rigidity, akinesia, bradykinesia, rest tremor, postural abnormalities, and speech dysfunction (Brodal, 1998; Marsden, 1994). Although the progression and severity of the disease can be considerably variable among individuals with PD, the fundamental motor symptoms of rigidity, tremor, and bradykinesia appear with relative consistency.

Treatment

Treatment options for individuals with PD include surgery, deep brain stimulation, and pharmacological treatments. Surgery for individuals with PD may include the creation of lesions in the thalamus (thalamotomy) or in the globus pallidus (pallidotomy). Both surgical techniques attempt to restore the balance of excitation and inhibition in the basal ganglia and thalamic circuits (Marsden & Obeso, 1994). This neurosurgery has been shown to relieve rigidity and tremor in PD; however severe side effects and dangers may occur during and following this
invasive procedure. A more recent neurosurgical treatment option is deep brain stimulation, where a high frequency stimulator is placed in the subthalamic nucleus, globus pallidus, or thalamus. This stimulator creates a functional lesion that has effects similar to a lesion but is somewhat reversible and less risky (Bjarkam, Sorensen, Sunde, Geneser, & Ostergaard, 2001). Deep brain stimulator implantation has been shown to have positive results on overall movement (Schulz & Grant, 2000) and often speech function (Tornqvist, Schalen, & Rehncrona, 2005), although some patients experience speech and voice problems resulting from the implantation and stimulation (Barlow, Hammer, Pahwa, & Seibel, 2003; Tornqvist et al., 2005). Overall, not all patients are candidates for neurosurgical treatment, and the neurosurgery is not without risks.

A more common (and often more well-tolerated) treatment option for individuals with PD is the dopamine-enhancing drug levodopa. The standard preparation (Sinemet) combines levodopa with carbidopa, which improves the absorption of levodopa and reduces some of its side effects, particularly nausea (Lang & Lozano, 1998b). During the initial 2-5 years after starting levodopa-related therapy, the drug consistently reduces the symptoms associated with PD (Djaldetti & Melamed, 1998) and this is often referred to as the ‘levodopa honeymoon period.’ After this period of time, individuals with PD may experience motor side effects and fluctuations in motor performance (Lang & Lozano, 1998b). Individuals with PD may experience times when their levodopa medication works well (ON state) and periods when there is a sudden or gradual loss of medication effectiveness (OFF state; Goberman & Coelho, 2002b). Sudden losses of effectiveness of levodopa may occur unrelated to changes in treatment schedule, which may improve spontaneously without an additional dose of levodopa. These unpredictable, rapid fluctuations have been defined as the “ON-OFF effect” (Djaldetti & Melamed, 1998).
A second motor fluctuation associated with levodopa is called the “wearing off” effect (Lang & Lozano, 1998b). As a result of the brain’s decreased ability to store dopamine, this “wearing off” effect is evidenced in a decreased length of effectiveness for each time levodopa is taken (Hurtig, 1997). Bradykinesia, dystonia, and dyskinesia may occur more frequently as a result of the drug lasting for shorter periods of time. Although fluctuations and side effects result from the combination of levodopa and the progression of PD, the benefits are irrefutable and levodopa remains the treatment of choice for PD therapy (Goberman & Coelho, 2002).

**PD Phonation**

The motor deficits associated with PD adversely affect the major systems that govern speech motor control including respiration, phonation, and articulation. The speech deficits related to PD are often called hypokinetic dysarthria and can be characterized by reduced vocal loudness, monopitch, reduced stress, slow speaking rate with short rushes of speech, prolonged syllables, long pauses, and reduced phonation time (Duffy, 1995; Dworkin, 1991). Specific to phonation, studies have been completed examining fundamental frequency ($F_o$), $F_o$ variability in vowel production, and intensity. Mean $F_o$ values in reading have been found to be higher for individuals with PD compared to controls (i.e., Canter, 1963; Goberman, Coelho, & Robb, 2002; Metter & Hanson, 1986). Goberman et al. (2002) examined the characteristics of nine PD participants’ speech compared to age and gender-matched control participants. Statistical analyses revealed that mean $F_o$ values were higher in the PD group compared to controls. Similarly, Metter and Hanson (1986) found that mean $F_o$ continued to increase as the severity of PD increased. This increase in $F_o$ found for PD patients is often attributed to rigidity of the laryngeal musculature, which results in increased stiffness of the vocal folds (Canter, 1963). In
addition to F\textsubscript{o} changes in reading, Goberman et al. (2002) also found increased F\textsubscript{o} variability in vowels along with a decreased intensity range in the PD group compared to controls. To further examine phonation, Goberman and Blomgren (in press) examined the offset and onset of phonation before and after a voiceless consonant in nine individuals with PD. The F\textsubscript{o} analysis at phonatory offset supported previous conclusions that individuals with PD have difficulty with the rapid offset of voicing. The F\textsubscript{o} analysis at onset revealed that controls and individuals with PD used some laryngeal tension to initiate voicing. The tension appeared highest in control participants and PD participants ON medication, and the tension appeared to be the lowest in the PD participants OFF medication, but no statistically significant differences were found. This may be a result of variability in the OFF medication state. Phonation research on individuals with PD has found that individuals with PD exhibit variability in F\textsubscript{o} and timing of voicing.

**PD Articulation**

Individuals with PD may exhibit articulation deficits as a component of hypokinetic dysarthria. A number of researchers have reported that individuals with PD demonstrate difficulties in articulation, including studies of oral closure for stop consonant production and studies of rapid alternating articulatory movements. For example, Ackermann and Zeigler (1991) reported that individuals with PD produced imprecise stop consonants during speech. The intensity of stop consonant production in twelve individuals with PD was compared to twelve control participants. Results indicated that the control participants exhibited decreased intensity at the moment of oral stop closure, whereas the individuals with PD did not show any decrease in intensity during oral stop closure. Complete closure may not have been achieved in individuals with PD due to reduced amplitude of articulatory movement or reduced articulatory
strength, leading to inability to fully close off the oral cavity during stop consonant production (Ackermann & Zeigler, 1991).

Deficits in articulator control and mobility may also affect the ability of individuals with PD to produce oral diadochokinetic (DDK) tasks. DDK tasks involve the production of syllable strings with consonant-vowel combinations at bilabial, alveolar, and velar places of articulation. For example, the rates of /papapap/..., /tapata.../, and /kapakaka.../ are used to examine an individual’s ability to make rapidly alternating articulatory movements (Shipley & McAfee, 1992). DDK rate tasks may be affected in individuals with PD due to a trade-off between decreased amplitude of articulator movement and rate of speech (Ackermann, Hertrich, & Hehr, 1995; Ackermann, Konczak, & Hertrich, 1997). Ackermann et al. (1997) examined DDK rates in two individuals with PD and reported that they had unimpaired DDK rates, but the individuals maintained a normal rate by reducing the amplitude of articulatory movement (articulatory undershoot). The individuals with PD compensated for slow movement of the articulators by decreasing the range of articulatory movements. Ackermann et al. (1995) reported similar findings for seventeen individuals with PD, as some patients used articulatory undershoot to compensate for slowed movement. However, the more severely affected individuals with PD produced abnormally slow speech in spite of their attempts to compensate by reducing their amplitude of articulation movement (Ackermann et al., 1995). Overall, deficits in articulation may be present in individuals with PD, as articulator control and range of motion may be affected by PD.
**PD Prosody**

A number of studies have found that impaired speech prosody can occur in individuals with PD. One method of examining speech prosody is to examine fundamental frequency fluctuations in sentences. Canter (1963, 1965) examined speech production in 17 PD males and found a decreased fundamental frequency range during both syllable production and reading paragraphs. Metter and Hanson (1986) investigated fundamental frequency variability during a reading passage and found a significant decrease in fundamental frequency compared to normal speakers. The variability decreased even more as the severity of PD increased. Flint, Black, Campbell-Taylor, Gailey, and Levinton (1992) also found a decreased fundamental frequency range for thirty individuals with PD compared to normal speakers during a reading task. Overall, these studies indicate a significantly reduced fundamental frequency range and variability in individuals with PD during speech tasks.

Prosodic intensity changes have also been studied in PD research. Caekebeke, Jennekens-Schinkel, Van der Linden, Buruma, and Roos (1991) examined emotion-related intensity changes in twenty-one PD individuals and controls. The participants produced sentences containing varying emotional feelings (i.e. angry, happy, neutral). Results indicated that the PD individuals produced smaller intensity changes than the controls and that the greatest difference occurred in sentences using the emotion anger. PD individuals did not produce the necessary intensity changes to indicate anger. Prosodic intensity deficits could have been an emotional problem as well as the possibility of a prosody problem. Metter and Hanson (1986) also reported a decreased ability for individuals with PD to produce intensity changes during speech. Participants with PD produced significantly smaller intensity variation compared to
normal speakers during the reading of a standard passage. To date, individuals with PD show a reduced ability to use pitch and intensity changes while reading to indicate different emotions.

**PD Speech Rate**

Although much is known about prosody of speech for individuals with PD, there are some areas, such as speech rate, where controversies still exist. Individuals with PD have been shown to exhibit rate abnormalities, causing speech rate either to be accelerated or slowed. Because planning and control of the articulators are required to produce speech, and individuals with PD may have deficits with motor control and rhythm, speech rate may be adversely affected. A number of studies have found that individuals with PD present with abnormally rapid rates of speech (e.g., Canter, 1967; Hirose, 1986; Solomon & Hixon, 1993). A possible explanation for this increase in rate includes the possibility that individuals with PD present with difficulty stopping voluntary movements once started (Canter, 1967; Hirose, 1986). A similar increase in speech rate was found by Solomon and Hixon (1993) in a study of the speech breathing of fourteen males with PD compared to fourteen controls. Based on a reading sample, Solomon and Hixon (1993) found an increased articulation rate along with a faster interpause speech rate than controls. The researchers noted that the mechanism for abnormal speech rate in PD is not known and results of previous research on the effect of medication on speech rate are mixed.

Other studies have found no significant differences of speech rate in individuals with PD compared to controls (e.g., Canter 1963; Metter & Hanson, 1986). Canter (1963) calculated words per minute (wpm) during a study of 17 males with PD who read the “Rainbow Passage”. Taking into account pausing, phrasing, and syllable duration, results indicated there was no
difference in speaking rate in the PD group compared to controls. Metter and Hanson (1986) found similar results when they examined speaking rate in eight individuals with PD while reading aloud the “Grandfather Passage”. When compared to controls, subjects exhibited rate on a continuum from much slower (77 wpm) than normal to much faster (263 wpm) than normal speaking rates. Furthermore, rate did not relate to either the severity of clinical symptoms or severity of dysarthria. Participants with mild parkinsonism and those with severe parkinsonism exhibited both slow and very rapid rates.

Even though the above studies have found an increase or no difference in PD speech rate compared to controls, one study by Ludlow, Connor, and Bassich (1987) noted that individuals with PD exhibited a decreased rate of speech. Twelve participants with PD and twelve control participants produced sentences and repeated syllables at “regular” and “fast” speaking rates. The control participants in the study were able to increase speech rate by reducing pauses between phrases, increasing the rate of words within a phrase, and reducing word and syllable durations; however the PD group was unable to alter speech timing during phrases and sentences and exhibited a decreased speech rate. The PD group was significantly impaired on speech duration during sentence and phrase production, suggesting that they have poor control over the duration of speech events. Overall, research indicates that speech rate is varied in individuals with PD, and the mechanisms for speech rate differences are still unknown.

**PD Speech and Levodopa Fluctuations**

Even though levodopa is seen as the gold standard for pharmacological treatment of PD, individuals with PD still experience fluctuations in performance when taking this medication. A number of studies have investigated the effect of levodopa-related fluctuations on speech and
voice production. These have included studies of phonation (Goberman et al., 2002; Sanabria et al., 2001), vowel production (Poluha, Teulings, & Brookshire, 1998), and rate (Solomon & Hixon, 1993; Goberman, Coelho, & Robb, 2005). Goberman et al. (2002) found that, when compared to age-matched control participants, individuals with PD demonstrated decreased intensity range, increased fundamental frequency variability in vowels, and increased mean fundamental frequency. When the participants were examined in their ON versus OFF states, group differences were not significant, but speech improvements were noted in individual participants (Goberman et al., 2002). Sanabria et al. (2001) examined sustained vowel productions for 20 individuals with PD before and after levodopa administration. Results indicated that levodopa is able to improve vocal performance in patients with PD. The improvements in tremor, noise, and fundamental frequency after the administration of levodopa may be attributed to a decrease in laryngeal hypokinesia and rigidity (Sanabria et al., 2001). These studies show that levodopa may have a positive effect on vocal quality in individuals with PD.

In addition to the studies on levodopa and phonation, one study examined vowel duration in individuals with PD. Poluha et al. (1998) measured the duration of the vowels /i/, /u/, /æ/, and /ɑ/ along with the dipthong /ai/ in single syllable words read aloud by 10 males with PD. Results indicated that vowel duration did not show significant differences across the medication cycle. However, the reading task in this study may have resulted in a better than normal speech performance because dysarthric speech is typically more impaired in spontaneous utterances (Yorkston & Beukelman, 1978).

Only two studies are known to have examined the effect of levodopa fluctuations on measures of articulation rate. Goberman et al. (2005) conducted a study of the effect of
levodopa-related fluctuations on measures of articulation rate in nine individuals with PD. Participants read a paragraph and produced a monologue before the administration of levodopa, and produced the same tasks one hour and two hours after the administration of levodopa. No significant differences in articulation rate in the OFF medication versus ON medication states were shown, indicating that articulation rate was unaffected by levodopa. However, Solomon and Hixon (1993) found that levodopa may have an effect on measures of speech rate. They examined the speech of 14 males with PD at the middle and end of their drug cycle. The individuals were perceptually judged to exhibit a fast speech rate, inappropriate pausing, and monopitch in the ON medication state. Quantitative results also showed that articulation rate was faster at the “wearing off” levodopa stage compared to the middle of the cycle. These results support the conclusion that speech rate was increased by the administration of levodopa.

**Voice Onset Time**

In addition to studies of articulation, voicing, and rate characteristics in individuals with PD, some studies have examined Voice Onset Time (VOT) in individuals with PD. Voice onset time is defined as the interval between the initial articulatory release of a stop consonant and the onset of voicing for the subsequent vowel (Kent & Read, 2002). The voiced stop consonants /b/, /d/, and /g/ have relatively short VOT values ranging from about -20 ms to +20 ms, while the voiceless stop consonants /p/, /t/, and /k/ have relatively long VOT values ranging from about 25 ms to as much as 100ms (Kent & Read, 2002; Lisker & Abramson, 1964). VOT serves as a voicing feature when stops are in syllable-initial position while VOT is also affected by place of consonant articulation and height of the following vowel. Related to place of articulation, it has been found that bilabial stops have the shortest VOTs, including frequent prevoicing; alveolar
stops have intermediate VOTs; and velar stops have the longest VOTs (Kent & Read, 2002). Specific to vowel height, Klatt (1975) found that VOT was longer for high vowels compared to lower vowels.

A number of other factors can influence this interval period between the release of constriction and onset of voicing, including age, rate of speech, phonetic context and lung volume at speech initiation (Allen, Miller, & DeSteno, 2003). Of these factors, the effect of rate on VOT has been examined in a large number of studies (e.g. Allen & Miller, 1999; Kessinger & Blumstein, 1997, Kessinger, & Blumstein, 1998). Acoustic measures of VOT reveal that voiced and voiceless consonants are not equally affected by changes in speaking rate (Miller, Green, & Reeves, 1986; Summerfield, 1981). Specifically, Miller at al. (1986) found that although VOT values for both /bi/ and /pi/ increased as speaking rate decreased, the effect of speaking rate was significantly less in the case of the voiced stop. The second important finding from this study was that as syllable duration increases, the difference between the /b/ VOT and /p/ VOT distribution also increases. Allen and Miller (1999) found similar results in a study on the effects of syllable-initial voicing and speaking rate. They measured the segmental durations for matched monosyllabic words beginning with voiced and voiceless stops and found that the change from voiced to voiceless stops produced increases in VOT, as well as an increase in vowel duration. These studies confirm that as speaking rate decreases and overall syllable duration increases, there is an increase in the VOT value of the voiceless stop, along with a similar (but reduced) increase in the VOT of the voiced stops.
Voice Onset Time in PD

The small body of research on VOT length in individuals with PD has shown varied results. Forrest, Weismer and Turner (1989) found an increase in VOT for the consonant /b/ in individuals with PD compared to age-matched participants, specifically in the initial position of words. They recorded productions of initial and medial position stop consonants /b/ and /p/ in nine individuals with PD, and they found that the VOTs for the initial /b/ productions were 7-9 msec longer for the individuals with PD compared to controls. Even though there were significant differences in VOT values for /b/, there were no significant differences between each group in the production of the voiceless equivalent /p/. The authors attributed the longer VOTs displayed by the individuals with PD for the voiced /b/ to the difficulty initiating and coordinating laryngeal movements (Forrest et al., 1989).

A study by Bunton and Weismer (2002) analyzed word-initial voiced-voiceless contrasts in nine word pairs in 10 individuals with PD, 10 individuals with amyotrophic lateral sclerosis, 5 individuals with a history of cerebrovascular accident, and 10 age-matched controls. Comparisons between the disorder groups and controls showed that the VOT durations for the disorder groups overlapped with variability of the target productions for the controls. Although some VOT measurements were consistent with previous literature, some of the voiced consonants did not always have shorter VOTs than their voiceless counterparts. Differences in VOT between PD and the other disorder groups were not found, nor were there differences in VOT measurements between the PD group and normal group. Therefore, no clear differences were found in VOT when comparing individuals with PD to age-matched controls.

Other research has shown a decrease in VOT in individuals with PD (Flint et al., 1992; Weismer, 1984). Weismer (1984) examined the speech of three groups of male subjects (two
control groups: one group with five adults aged 21-27 and one group with eight adults aged 65-82; one experimental group: eight individuals with Parkinson disease). All participants produced sentences in a conversational style and twice as fast as their conversational rate. Analysis consisted of quantitatively measuring segment duration and qualitatively measuring closure intervals of stop consonants and vocal fold vibration after voiceless stops (to determine if vibration continued for more than 20msec after the stop). The greatest group difference for segment duration was found for the voiceless interval. The group with PD produced voiceless stops and fricatives that were shorter than the control groups. Weismer (1984) suggested that this decrease in VOT in the PD group was due to stiffness of the laryngeal musculature, causing a reduction in vocal fold opening. Weismer hypothesized that the patients with PD were therefore able to close their vocal folds more quickly than controls (decreasing VOT). This finding contradicts with Weismer’s more recent study (Forrest et al., 1989) that found increased VOT in PD due to impaired laryngeal movements. More research is warranted on VOT in individuals with PD to determine potential explanations for the above conflicting results.

Overall, VOT literature on PD shows that these individuals may exhibit deficits with the onset of voicing, but the direction and reasons for a VOT difference is still in question.

It is possible that these inconsistent findings for individuals with PD have stemmed from the fact that VOT has been examined independent of rate in these studies. Given that VOT has been shown to vary as a function of speech rate (Miller et al., 1986; Summerfield, 1981), and that individuals with PD have been known to have rate deficits, the validity of previous VOT results may be in question. Therefore, the current study examines VOT in individuals with PD based on two different measures: (1) the conventional VOT measure (VOT); and (2) VOT with the effect of rate removed (VOT Ratio). These measures are going to be used to answer the
following questions. First, is there a difference in VOT or VOT ratio when individuals with PD are compared to age-matched control participants? Second, is there any effect of PD medication on VOT and VOT ratio?
METHOD

Participants

This study was reviewed and approved by the Human Subjects Review Board at Bowling Green State University. Four females and 6 males aged 48-80 completed the informed consent process (Appendix A), and participated in the study. All participants met the following selection criteria: (1) diagnosed with idiopathic PD; (2) treated with Sinemet or Sinemet CR and potentially other antiparkinsonian medications; (3) reported fluctuations in response to medication(s); (4) native speakers of American English; (5) no reported neurological surgeries, neurological diseases; and (6) no reported previous speech, language, or hearing disorders unrelated to their Parkinsonian symptoms. Participant characteristics can be found in Table 1. One participant with PD (Participant 10) was eliminated from the study because the required measurements could not be completed. Throughout this participant’s speech sample, stop consonant release bursts were not evident, vowels were weak and without observable glottal pulses, and continuous voicing often occurred due to the severity of his dysarthria.

Nine control participants, matched for age (within 11 months) and gender with the PD participants, were also recorded. All control participants had no history of speech, language, or hearing disorders and had no neurological diagnoses or neurological surgeries.
Table 1: PD Participant Characteristics. Medication effectiveness in the OFF state and ON state was rated by the participants on a scale of 1 to 7, where 1=not at all and 7=perfectly. A similar scale for symptom severity was used, where 1=extreme and 7=None.

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<td>10 *</td>
<td>74</td>
<td>Male</td>
<td>8</td>
<td>5</td>
<td>5</td>
<td>6</td>
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<tr>
<td><strong>MEAN</strong></td>
<td>65.6</td>
<td></td>
<td></td>
<td><strong>9.7</strong></td>
<td><strong>4.0</strong></td>
<td><strong>5.8</strong></td>
</tr>
</tbody>
</table>

* Note: Participant 10 was eliminated from the study because VOT values were not identifiable (see text).
Protocol

Each participant with PD was recorded twice in their home. The first recording took place 30 minutes before administration of their normal morning PD medications (after withdrawing from medication for at least 8 hours during the previous night). This recording represented a practically-defined OFF medication state (Defer, Widner, Marie, Remy, & Levivier, 1999), and participants provided their own estimate of medication effectiveness and disease symptom severity at that time. The second recording happened on the same day, 60 minutes after their morning medication administration. This represented an ON state, and again was verified by participants’ own estimates of disease symptom severity and medication effectiveness (Appendix B). Previous research (Goberman, Elmer, Mackowiak, & Heaton, 2004) has found a good correlation between self-ratings of medication effectiveness and disease symptom severity, and comprehensive testing of motor behavior (in both ON and OFF medication states).

The control participants were recorded once each. Seven of the nine control participants were recorded for a different study; however the VOT stimuli, recording equipment, and microphone were the same for both studies. All control participants were asked to read the stimuli at their normal rate, pitch, and loudness levels.

Dysarthria Assessment

At the beginning of the first recording session for the PD group, participants were asked to produce three different tasks in order to assess the severity and type of dysarthria they were exhibiting. The first task was a reading of the Rainbow passage (Fairbanks, 1960). The second task was a diadochokinetic (DDK) rate task. For this task, participants were asked to produce the
syllable strings /papapap…/, /tattatt…/, /kakkaka…/, and /patak-patak-patak-patak-patak…/ as fast and steady as possible. Modeling was provided if needed. The final task was a prolongation of the vowel “/a/” as long and steady as possible on one breath. Appendix C provides the directions and stimuli that were used for the dysarthria assessment. Based on these three tasks, dysarthria type and severity was evaluated using criteria determined by Darley, Aronson, and Brown (1969). This evaluation was completed by an ASHA-certified Speech-Language Pathologist with experience working with individuals with PD.

**Stimuli**

Both the PD group and control group produced a series of phrases for assessment of VOT. The phrase “CVp again” was used, where the C represented stop consonants and V represented the corner vowels. Specifically, the phrases consisted of three initial voiced stop consonants /b/, /d/, and /g/ and three initial voiceless stop consonants /p/, /t/, and /k/ each followed by the four corner vowels /i/, /u/, /a/, /æ/. The order of consonant presentation, as well as the order of the four vowels after each consonant was randomized. Appendix D provides the stimulus materials and directions that were used for this task. Each phrase was repeated twice during each recording session, for a total of 48 phrase productions by each control participant (during their one recording session), and 96 phrase productions by each individual with PD during two recording sessions (48 phrases during the OFF state and 48 phrases during the ON state).
Recording and Acoustic Analysis

Data was collected using a Shure SM-58 microphone and a Digital Audio Tape recorder (Sony PCM-M1). The microphone was on a tabletop stand, and the distance between the mouth and microphone was 15 cm throughout the recording. The speech samples were digitized with KAY CSL 4400 software/hardware package, and analyzed using the PRAAT software package (Boersma & Weenink, 2007). Background noise levels were checked with a BK Precision sound level meter and were below 40 db-A during all recordings (average of 32.39 db-A).

VOT Measurement

VOT was determined by measuring the interval from the onset of the initial stop burst to the onset of periodicity associated with the vowel. This interval was measured directly from a coupled raw waveform and wide-band spectrogram displaying both the initial stop consonant for the burst and the subsequent vowel (see Figure 1). Vertical cursors were placed at these two time points and the time between the cursors was calculated as the VOT. If multiple bursts were present in the initial stop consonant, the initial burst was used to measure VOT (Wang, Kent, Duffy, Thomas, & Weismer, 2004; see Figure 2). Note that VOT was measured from stop consonants in the phrase initial position because previous studies have shown that individuals with PD have the most significant VOT deficits in the initial position of sentences (Forrest et al., 1989).
Figure 1: Voice Onset Time (VOT) measurement for /pip/. The shaded area displays measurement from the onset of the initial consonant /p/ to the onset of periodicity associated with the /i/. VOT = 0.060 sec.
Word Duration

Word duration served as the primary measure of the speaking rate at which the word was produced. Word duration was measured as the interval from the onset of the initial stop burst to the offset of energy associated with the vowel (see Figure 3). To maximize measurement reliability, the post-vocalic consonant was not included in this measurement. This analysis of speaking rate (and the use of the term ‘word duration’) corresponds with the rate measurement used in previous studies (Allen et al., 2003; Volaitis & Miller, 1992). For example, in the phrase “pop again” seen in Figure 3, word duration is 0.236 seconds, based on the measurement from 12.107 seconds to 12.343 seconds in the word “pop”. Speaking rate was measured from each phrase production produced by the control participants and participants with PD.
Specific Measurement Criteria

Measurements of burst onset and the end of the vocalic nucleus are sometimes challenging in dysarthric speech. Therefore, measurement criteria were established as follows:

1. VOT was not measured when (1) a release burst was not evident, (2) the vowel was weak and without observable glottal pulses, and (3) continuous voicing took place (Wang et al., 2004).

2. The end of the vocalic nucleus was determined by the presence of the first formant (F1) combined with energy of a higher format (F2 or F3) (Allen et al., 2003; Volaitis & Miller, 1992; Wang et al., 2004).
3. If double or multiple bursts were present in the initial stop consonant, the initial burst was used to measure VOT (Wang et al., 2004).

**VOT Ratio**

Given that VOT varies as a function of speech rate (Miller et al., 1986; Summerfield, 1981), statistical analysis was also completed by using a ratio of VOT to word duration. This measurement was used to analyze VOT independent of rate changes. The VOT ratio for each production was calculated by dividing the VOT of each syllable by the duration of that syllable (Ravizza, 2003).

\[
\text{VOT Ratio} = \left[ \frac{\text{VOT (in msec)}}{\text{word duration (in msec)}} \right]
\]

**Reliability**

To determine intrajudge reliability of the VOT measures, three speech samples (144 phrases) were re-analyzed by the same researcher. This constitutes 11% of the data. The three samples included one control recording and two PD recordings. Inter-judge reliability was assessed by having a second researcher analyze the same three recordings assessed above. For the measurement of VOT, pearson-product moment correlation (PPMC) analysis revealed high intrajudge reliability \((r=0.998; p<0.001)\), and high interjudge reliability \((r=0.963; p<0.002)\). In addition, the average VOT measurement difference for intra- and interjudge reliability was 0.0007 sec, and 0.0039 sec respectively. For the measurement of word duration, PPMC analysis revealed high intrajudge reliability \((r=0.993; p<0.001)\), and high interjudge reliability \((r=0.993; p<0.001)\). The average word duration measurement difference for intra- and interjudge reliability was 0.00129 sec, and 0.001036, respectively.
Statistics

Three statistical analyses were made based on the dependent variables (VOT and VOT Ratio) using a mixed design multivariate analysis (MANOVA) for accurate analysis. The first comparison was the control participants versus the PD participants OFF medication. The second was the control participants versus the PD participants ON medication, and the third comparison was a comparison of the PD participants OFF medication versus ON medication. A description of the statistical analysis follows, with a summary given in Table 2.

The MANOVA was used for both the comparisons of the control participants to the PD participants OFF medication and the comparisons of the control participants to the PD participants ON medication. The between factor for both of these tests was state, which included the control participants versus PD participants ON medication or the control participants versus PD participants OFF medication. There were two repeated (within) factors for each test. The first within factor was place of articulation (3 levels: bilabial, alveolar, and velar). The second factor was vowel height (high versus low). These analyses were completed separately for voiced and voiceless stops.

A Repeated-Measures Analysis of Variance (RMANOVA) was used for the comparison of the PD participants OFF medication versus ON medication. Three within factors were analyzed in this test. The first within factor was state (ON medication versus OFF medication) and the second within factor was place of articulation (3 levels: bilabial, alveolar, and velar). The third within factor was vowel height (high versus low). Data were again analyzed separately for voiced and voiceless stops.

The rationale for the choice of independent variables was based on a review of pertinent literature. The effect of consonant placement (bilabial, alveolar, velar) has been shown to have
an effect on VOT. Kessinger and Blumstein (1997) conducted a study on the effects of speaking rate on VOT in Thai, French, and English. The results of the study found that bilabial stop consonants have shorter VOT values than alveolar stops in English. This corresponds with previous research on the effect of place of articulation on VOT in stop consonants (Lisker & Abramson, 1964). As a result of these findings, consonant place of articulation is examined as an independent variable in the current study.

Vowel height was also included as an independent variable because it influences VOT. The VOTs of stop consonants vary as a function of phonetic and suprasegmental characteristics. VOTs of voiceless plosives are lengthened by approximately 15% before high the high vowels /i, u/ as compared with the low vowels /a, æ/ (Klatt, 1975, Port & Rotunno, 1979; Weismer, 1979).

Finally, group and medication effects were examined because previous literature has reported voice related changes between individuals with PD and controls. Variability in vowel and stop consonant production, intensity, and F₀ have been found in individuals with PD compared to controls (i.e. Ackermann & Zeigler, 1991; Canter, 1963; Goberman et al. 2002). Medication has also been shown to affect voice related changes in individuals with PD. Levodopa has been shown to have an effect on vocal fold offset and onset behavior (Goberman and Blomgren, in press).
Table 2: Statistical Analyses.

PD participants OFF medication versus Control participants
- Dependent variables
  - VOT
  - VOT Ratio
- Independent variables:
  - Within: Place of articulation (bilabial versus alveolar versus velar)
  - Within: Vowel height (high versus low)
  - Between: State (OFF versus Controls)

PD participants ON medication versus Control participants
- Dependent variables
  - VOT
  - VOT Ratio
- Independent variables:
  - Within: Place of articulation (bilabial versus alveolar versus velar)
  - Within: Vowel height (high versus low)
  - Between: State (ON versus Controls)

PD participants OFF medication versus PD participants ON medication
- Dependent variables
  - VOT
  - VOT Ratio
- Independent variables:
  - Within: Place of articulation (bilabial versus alveolar versus velar)
  - Within: Vowel height (high versus low)
  - Within: State (ON versus OFF)
  - Between: None

* Statistical analyses of each comparison were completed separately for voiced and voiceless sounds.
RESULTS

Medication Effectiveness and Dysarthria Ratings

Dysarthria severity ratings were completed to determine if participants exhibited hypokinetic dysarthria which is typical of individuals with PD. Results indicated that all participants exhibited hypokinetic dysarthria in their OFF medication state. The participants’ hypokinetic dysarthria ranged from mild to severe (5 mild, 3 moderate, and 1 severe).

In addition to dysarthria severity ratings, each participant rated his or her own medication effectiveness in the OFF and ON state (1=not at all and 7=perfectly), as well as their perceptions of symptom severity (1=extreme and 7=none). Participants’ self-report of medication effectiveness in ON and OFF states were used to determine if they were receiving benefit from their medication. Overall, six of the nine participants reported improved symptoms when they were ON medication. In addition, six of the nine participants reported improved medication effectiveness when ON medication. On average, medication effectiveness increased from 4.0 to 5.8 from the OFF to the ON state, while symptom severity increased from a 3.8 to 5.2. Results of the PD participants’ medication effectiveness and symptom severity, as well as their dysarthria severity rating are listed in Table 1.

PD OFF Medication vs Controls

Voiceless: Multivariate MANOVA testing of voiceless sounds for the PD participants OFF medication versus the control participants revealed significant multivariate main effects for Place [F(4,64)=9.554; \(p<0.001; \eta^2=0.374\)] and Height [F(2,15)=68.752; \(p<0.001; \eta^2=.902\)]. Univariate statistics revealed that both place and height main effects were significant for both VOT and VOT ratio. There was no multivariate group (PD OFF vs. Control) main effect.
[F(2,15)=0.254; \( p=0.779; \eta^2=0.033 \)], and there were no multivariate interactions (see Table 3 for a summary of PD OFF vs Control statistical results). For vowel height, the high vowels had longer VOT and VOT ratio values compared to the low vowels. Post-hoc testing was completed to further examine the main effect of place. Post-hoc paired-samples t-tests (\( p \)-level adjusted to 0.0083) revealed that bilabial sounds had the significantly shorter VOT compared to both alveolar and velar sounds, and alveolar sounds had shorter VOT than velar sounds. For VOT Ratio, bilabial sounds were significantly shorter than velar sounds, and alveolar sounds were significantly shorter than velar sounds. All VOT and VOT ratio means data for all comparisons is listed in Table 4.

**Voiced:** Multivariate MANOVA testing of voiced sounds (See Table 3) for the PD participants OFF medication versus the control participants revealed no significant multivariate main effects for Place [F(4,64)=2.159; \( p=0.084; \eta^2=0.119 \)], Height [F(2,15)=3.077; \( p=0.076; \eta^2=0.291 \)], or Group [F(2,15)=2.125; \( p=0.154; \eta^2=0.221 \)]. A significant multivariate Place X Height interaction [F(4,64)=2.704; \( p=0.038; \eta^2=0.145 \)] was found, and this was supported with a significant univariate interaction for VOT only. Post-hoc univariate ANOVA testing of this interaction revealed that high vowels had significantly more negative (i.e., more prevoiced) VOTs than low vowels at the alveolar [F(1,16)=4.986; \( p=0.040; \eta^2=0.238 \)] and velar places of articulation [F(1,16)=10.962; \( p=0.004; \eta^2=0.407 \)], but not at the bilabial place of articulation [F(1,16)=0.186; \( p=0.672; \eta^2=0.011 \)].
Table 3: PD OFF Medication vs Controls Results.

<table>
<thead>
<tr>
<th>PD OFF Medication vs. Controls</th>
</tr>
</thead>
<tbody>
<tr>
<td>State</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td><strong>Voiceless</strong></td>
</tr>
<tr>
<td>Multivariate</td>
</tr>
<tr>
<td>VOT</td>
</tr>
<tr>
<td>VOT Ratio</td>
</tr>
<tr>
<td><strong>Voiced</strong></td>
</tr>
<tr>
<td>Multivariate</td>
</tr>
<tr>
<td>VOT</td>
</tr>
<tr>
<td>VOT Ratio</td>
</tr>
</tbody>
</table>

Note: - = no statistical significance.
Table 4: VOT and VOT Ratio Means

<table>
<thead>
<tr>
<th></th>
<th>CONTROL</th>
<th></th>
<th></th>
<th>PD OFF</th>
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<th>PD ON</th>
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<td>Voiceless</td>
<td>Voiced</td>
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<tr>
<td>Bilabial</td>
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<td></td>
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</tr>
<tr>
<td>VOT</td>
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<td></td>
<td></td>
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<td></td>
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<tr>
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<td>.0492</td>
<td>-.0136</td>
<td>.0417</td>
<td>.0044</td>
</tr>
<tr>
<td>VOT Ratio</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>.0443</td>
<td>.2644</td>
<td>-.1227</td>
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<td>-.0008</td>
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<td>VOT Ratio</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High</td>
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<td>.3573</td>
<td>-.0485</td>
<td>.3395</td>
<td>-.1057</td>
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<td>VOT</td>
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</tr>
<tr>
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<td>.0753</td>
<td>.0108</td>
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<td>.0163</td>
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<td></td>
</tr>
<tr>
<td>High</td>
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<td>.4316</td>
<td>.0527</td>
<td>.4201</td>
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<tr>
<td>Low</td>
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<td>.0752</td>
<td>.3290</td>
<td>.0753</td>
<td>.3188</td>
<td>.0935</td>
</tr>
</tbody>
</table>
PD ON Medication vs Controls

**Voiceless:** Multivariate MANOVA testing of voiceless sounds for the PD participants ON medication versus controls revealed no multivariate group (PD ON vs. Control) main effect \[ F(2,15)=1.954; \ p=0.176; \ \eta^2=0.207 \], and there were no multivariate interactions (See Table 5). Significant multivariate main effects were found for Place \[ F(4,64)=10.888; \ p<0.001; \ \eta^2=0.405 \] and Height \[ F(2,15)=19.933; \ p<0.001; \ \eta^2=0.727 \]. Univariate testing revealed that Place main effects were significant for VOT and VOT ratio, while Height main effects were significant for VOT ratio only. For vowel height, the low vowels had shorter VOT and VOT ratio values compared to the high vowels. Post-hoc paired-samples \( t \)-tests (\( p \)-level adjusted to 0.0083) revealed that bilabial sounds had significantly shorter VOT compared to both alveolar and velar sounds, and alveolar sounds had shorter VOT than velar sounds. Similar results were found for VOT Ratio except bilabial sounds were not significantly different than alveolar sounds for high vowels (\( p=0.076 \)).

**Voiced:** Multivariate MANOVA testing of voiced sounds for the PD participants ON medication versus the control participants (See Table 5) revealed no significant multivariate main effects for Group \[ F(2,15)=2.191; \ p=0.146; \ \eta^2=0.226 \]. Significant multivariate main effects were found for Place \[ F (4,64)=2.959; \ p=0.026; \ \eta^2=0.156 \] and Height \[ F(2,15)=5.548; \ p=0.016; \ \eta^2=0.425 \]. Univariate testing revealed that the Place main effects were significant for VOT and VOT ratio, while Height main effects were significant for VOT ratio only. A significant Place X Height multivariate interaction \[ F(4,64)=3.278; \ p=0.017; \ \eta^2=0.170 \] was determined, however there were no univariate main effects for VOT or VOT ratio. Post-hoc univariate ANOVA testing of this interaction was not completed because no univariate differences were found.
Table 5: PD ON Medication vs Controls Results

<table>
<thead>
<tr>
<th>PD ON Medication vs. Controls</th>
<th>State</th>
<th>Place</th>
<th>Height</th>
<th>Place X Height</th>
<th>Other interactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voiceless</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multivariate</td>
<td>-</td>
<td>p&lt;0.01</td>
<td>p&lt;0.01</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>VOT</td>
<td>-</td>
<td>p&lt;0.01</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>VOT Ratio</td>
<td>-</td>
<td>p&lt;0.01</td>
<td>p&lt;0.01</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Voiced</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multivariate</td>
<td>-</td>
<td>p&lt;0.05</td>
<td>p&lt;0.05</td>
<td>p&lt;0.05</td>
<td>-</td>
</tr>
<tr>
<td>VOT</td>
<td>-</td>
<td>p&lt;0.01</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>VOT Ratio</td>
<td>-</td>
<td>p&lt;0.01</td>
<td>p&lt;0.01</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Note: - = no statistical significance.

PD OFF Medication vs PD ON Medication

*Voiceless:* Multivariate RMANOVA testing of voiceless sounds for the PD participants OFF medication versus PD participants ON medication (See Table 6) revealed no significant multivariate interactions, however there were significant multivariate main effects for Place [F(4,32)=5.887; p=0.001; $\eta^2=0.424$], and Height [F(2,7)=23.580; p=0.001; $\eta^2=0.871$]. In addition there was a significant main effect for group [F(2,7)=10.787; p=0.007; $\eta^2=0.755$], indicating a PD OFF vs. PD ON medication difference. However, univariate group statistics revealed no significant effect for VOT (p=0.078; $\eta^2=0.337$) or VOT ratio (p=0.339; $\eta^2=0.114$).
Univariate statistics revealed that Place main effects were significant for both VOT and VOT ratio, and a univariate Height main effect was significant for VOT ratio only. For vowel height, the low vowels had shorter VOT and VOT ratio values compared to the high vowels. Post-hoc paired-samples $t$-tests (adjusted $p<0.0083$) revealed that bilabial sounds had significantly shorter VOT compared to both alveolar and velar sounds, and alveolar sounds had shorter VOT than velar sounds. Post-hoc paired samples $t$-tests for VOT ratio found that bilabial sounds had a significantly shorter VOT ratio than velar sounds for both high and low vowels, and alveolar sounds had a significantly shorter VOT ratio than velar sounds for low vowels only.

**Voiced:** Multivariate RMANOVA testing of voiced sounds for the PD participants OFF medication versus the PD participants ON medication (See Table 6) revealed no significant multivariate main effects for Place [$F(4,32)=1.656; p=0.185; \eta^2=0.171$], Height [$F(2,7)=0.501; p=0.626; \eta^2=0.125$], or Group [$F(2,7)=0.375; p=0.700; \eta^2=0.097$]. Furthermore, there were no significant multivariate interactions.
Table 6: PD OFF Medication vs PD ON Medication Results

<table>
<thead>
<tr>
<th>PD OFF Medication vs PD ON Medication</th>
</tr>
</thead>
<tbody>
<tr>
<td>State</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>Voiceless</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Voiced</td>
</tr>
<tr>
<td></td>
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<td></td>
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</tbody>
</table>

* Although there was a significant multivariate effect of State, there were no significant univariate effects. The p-levels are listed to show the difference between VOT and VOT ratio.

Control Participants

*Voiceless:* Multivariate MANOVA analysis of voiceless sounds for the control participants alone revealed a significant multivariate main effect of Place [$F(4,32)=5.732; p=0.001; \eta^2=0.417$] and Height [$F(2,7)=21.181; p=0.001; \eta^2=0.270$], and no multivariate interactions. Univariate statistics revealed that both place and height main effects were significant for both VOT and VOT ratio.
Voiced: Multivariate MANOVA analysis of voiced sounds for the control participants alone revealed a significant multivariate main effect of Height \([F(2,7)=5.031; p=0.044; \eta^2=0.590]\), but no significant multivariate main effect of Place \([F(4,32)=1.486; p=0.229; \eta^2=0.157]\). Univariate statistics revealed that height main effects were significant for both VOT and VOT ratio. In addition, there were no significant multivariate interactions for voiced sounds.
DISCUSSION

Previous research examining VOT in individuals with PD has shown higher VOT (Forrest et al., 1989), lower VOT (e.g. Weismer, 1984), and no change in VOT (Bunton & Weismer, 2002) compared to controls. Voice onset time research (in non-neurologically impaired individuals) has found that changes in speaking rate have an effect on VOT. However, most studies examining VOT in PD have not taken into account that individuals with PD are known to exhibit speaking rate differences. One study by Ravizza (2003) utilized an equation to account for differences in speaking rate. In analyzing VOT, the standard deviation of the formant transition duration for /b/ and /d/ productions was divided by the duration itself. Variability of transition duration tended to be higher for groups that included individuals with PD. To further examine possible VOT variability, the current study examined VOT in individuals with PD based on two different measures: (1) the conventional VOT measure (VOT); and (2) VOT with the effect of rate removed (VOT Ratio). These measures were used to answer the following two questions. First, is there a difference in VOT or VOT ratio when individuals with PD are compared to age-matched control participants? Second, is there any effect of PD medication on VOT and VOT ratio? In addition, effects of place and height on VOT were examined as a result of previous findings of a relationship between VOT and phonetic environment.

Effect of Place

Previous literature found that VOT is affected by place of consonant articulation. The current study found a significant effect of place of articulation, but this effect was found primarily for comparisons involving voiceless sounds. Specifically for voiceless sounds, the
VOT ratio and VOT durations were shortest for bilabial sounds, followed by alveolar sounds. The velar sounds had the longest VOT and VOT ratio values. This place effect held true for all three comparisons completed in this study: PD participants OFF medication versus control participants, PD participants ON medication versus control participants, and PD participants ON versus OFF medication. Although the place effect was strong for voiceless sounds, a similar place effect was found only for one of the three comparisons for voiced sounds (PD ON medication versus Controls). Overall, there was a significant effect of place of articulation primarily for voiceless sounds. Previous literature found a similar effect of place on VOT, as it has been found that bilabial stops have the shortest VOTs, including frequent prevoicing; alveolar stops have intermediate VOTs; and velar stops have the longest VOTs (Kent & Read, 2002; Kessinger & Blumstein, 1997; Lisker & Abramson, 1964).

Because the current data examined place within the context of group comparisons (Control participants and individuals with PD together), the current data were re-analyzed for the control participants alone. This allows for a more accurate comparison between the current non-neurologically impaired control participant data and previous normative data. When control participants were examined alone, a similar significant effect of place was found, but for voiceless sounds only. Klatt (1975) has proposed possible explanations for increased VOT as place of articulation is retracted in terms of articulatory dynamics. Klatt (1975) concluded that differences in VOT between labials, alveolars, and velars may be explained by observing the time course of the pressure developed across the oral closure following release. A labial release is quick and weak in intensity because there is no resonator in front of the lips, causing a short burst. Velar releases, however, involve the entire tongue with constriction increasing in area more slowly. This is due in part to the mass of the tongue as well as the fact that the release of
tongue motion is usually not perpendicular to the vocal tract. These factors contribute to whether the duration of VOT will be relatively short (labials and alveolars) or long (velars; Klatt, 1975).

**Effect of Height**

Vowel height has also been shown to affect the VOT of stop consonants. A significant effect of vowel height was found in the current study, but again this effect was found primarily for comparisons involving voiceless sounds. The VOT ratios of voiceless sounds were longer for high vowels compared to low vowels in all three comparisons in this study (PD participants OFF medication versus Controls, PD participants ON medication versus Controls, and PD participants ON versus OFF medication). A significant effect of vowel height on VOT for voiceless sounds occurred only in the PD OFF versus Control comparison. Similar to the place effect, a height effect for voiced sounds was found for only one of three comparisons (PD ON medication versus Controls). Furthermore, a place by height interaction for voiced sounds occurred in two comparisons (PD OFF medication versus Controls and PD ON medication versus Controls). Previous research on VOT and PD has only examined place of articulation, so there is no current literature on place and height effects together. Due to the high effect size of these analyses (average $\eta^2 = .883$), vowel height should continue to be examined in future VOT studies. Some research has collapsed means across vowel height (i.e., Allen & Miller, 1999) without closely examining the relationship between vowels and VOT. Overall, the current study found a significant effect of vowel height primarily for the VOT ratio of voiceless sounds. This corresponds with previous literature that has found a similar effect of vowel height where VOTs of voiceless plosives are lengthened by approximately 15% before high the high vowels /i, u/ as compared with the low vowels /a, æ/ (Klatt, 1975a, Port & Rotunno, 1979; Weismer, 1979).
Control participant data was examined again to allow for a more accurate comparison between the current control participant data and previous normative data. In the current study, a significant effect of vowel height was found for both voiced and voiceless sounds. Previous literature on non-neurologically impaired individuals has found a similar effect of vowel height on voiceless plosives. Klatt (1975) confirmed that the longer VOT for /p, t, k/ preceding a high vowel is consistent with a phonological rule of Japanese in which vowels become voiceless if surrounded by voiceless obstruents. High vowels seem to influence the movement of the larynx such that laryngeal fundamental frequency is higher and voicing is less easy to initiate than in other vowels (House & Fairbanks, 1953). Difficulties initiating voicing may explain the increased VOT for high vowels.

**Voiced vs Voiceless**

The majority of the significant comparisons in the study involved only the voiceless sounds. Although previous literature has stated that the VOT of both voiced and voiceless plosives is significantly longer before sonorants, the majority of the research has found significantly longer VOTs of voiceless plosives before high vowels compared to low vowels (Klatt, 1975a, Port & Rotunno, 1979; Weismer, 1979). There is very little overlap of the voiced and voiceless ranges, making the two categories quite distinct. One possible explanation for the lack of statistical significance for the voiced sounds includes variability. The standard deviations of the voiced sounds in the current study were higher than the voiceless sounds, and this might have contributed to the lack of statistical significance. Another possible explanation regards scaling. It is possible that statistical significance was easier to find for changes in voiceless sounds, because the magnitude of these values is larger. Alternatively, the small magnitudes
(and sometimes negative values) of the voiced VOT values may have made it more difficult to find statistical significance.

**PD vs Controls**

In the current study, there were no significant group effects for PD OFF versus Controls and PD ON versus Controls comparisons for both VOT and VOT ratio. This contradicts previous research on VOT which has shown an increase (Forrest et al., 1989) or a decrease in VOT (Weismer, 1984) for PD participants compared to controls. Forrest et al. (1989) found a significantly longer VOT in individuals with PD for the voiced sound /b/, but no significant VOT changes of its voiceless equivalent /p/. The authors attributed the longer VOTs displayed by the individuals with PD for the voiced /b/ to the difficulty initiating and coordinating laryngeal movements (Forrest et al., 1989). Weismer (1984), however, found that individuals with PD produced significantly shorter VOTs of voiceless sounds than controls. Weismer (1984) suggested that this decrease in VOT in the PD group was due to stiffness of the laryngeal musculature, causing a reduction in vocal fold opening. Weismer hypothesized that the patients with PD were therefore able to close their vocal folds more quickly than controls.

Bunton and Weismer (2002) found similar results to the current study of no changes in VOT for PD compared to controls. Voice onset time may not be different between the two groups because individuals with PD may be compensating for slow movement of the articulators by decreasing the range of articulatory movements. Ackermann et al. (1995) reported that some individuals with PD used articulatory undershoot to compensate for slowed movement. It is possible that the relatively mildly impaired participants in the current study were making articulatory changes to ensure that VOT remained accurate. Therefore, it is probable that
individuals who exhibit more severe hypokinetic dysarthria would exhibit more severe VOT deficits (as articulatory undershoot may no longer account for deficits in speed of articulatory movement). Future research should examine the effect of severity of dysarthria on VOT changes in individuals with PD.

**Effect of Medication**

In the current study, there was a significant multivariate effect of medication for voiceless sounds in the PD OFF vs PD ON comparison. No significant univariate effects were found for VOT or VOT ratio, however significance was stronger for VOT ($p=0.078; \eta^2=0.337$) than for VOT ratio ($p=0.339; \eta^2=0.114$). Even though the univariate difference was not significant, the VOT for participants ON medication was lower than the same participants recorded OFF medication. When the data was converted to VOT Ratio, this difference decreased. Because the changes in VOT were greater than the changes in VOT ratio, it can be concluded that the changes in VOT were related to a medication-related change in word-level articulation rate. Some previous research on the administration of levodopa and paragraph-level articulation rate has shown that no significant differences occurred between the OFF and ON states, indicating that paragraph-level articulation rate was unaffected by levodopa (Goberman et al., 2005). Other research has found that phrase-level speech rate is increased by the administration of levodopa (Solomon & Hixon, 1993). The current findings may be related to a similar rate change at the word-level, although rate was not examined as a dependent measure in the current study. In the current study, levodopa appears to cause speech changes in the ON state, however exact reasons for this change remain elusive.
Another possibility is that the current findings reflect a change in variability of VOT related to medication administration. There were more differences in VOT and VOT Ratio in the PD ON medication versus Control comparisons compared to the PD OFF medication versus Control participant comparisons. It is possible that this difference results from changes in the variability of VOT and VOT Ratio (therefore affecting statistical comparisons). De Letter, Santens, De Bodt, Boon and Van Borel (2006) found that levodopa administration caused no significant improvements of speech rate, but the variability of speech rate increased in the ON state.

**VOT vs VOT Ratio**

For a majority of the comparisons, the VOT and VOT ratio data tended to be fairly well correlated. For example, all of the significant place of articulation effects were significant for both VOT and VOT ratio. For these effects, it can be inferred that rate is not affected by place of articulation changes. However, there are a number of comparisons that were significant for VOT ratio but not for the traditional VOT measure. This occurred for most of the comparisons of high versus low vowels. For these comparisons, the elimination of rate from VOT ended up being an important manipulation. Recall that previous research found a correlation between rate and VOT for non-neurologically impaired individuals. Applying that result to the current data, it can be concluded that a true VOT difference was found related to vowel height, and that this difference was not the result of an articulation rate change.

One other difference was found between VOT and VOT ratio. For the examination of medication-related differences in individuals with PD OFF versus ON medication, a greater effect was found for VOT than for VOT ratio. Because the difference was decreased when the
data was converted to VOT ratio, it can be inferred that the difference was actually more reflective of a rate change, rather than a pure VOT change. Overall, the current data support the usefulness of examining both VOT and VOT ratio with individuals with PD, as this method allows for dissociation between rate-related changes and true VOT-related changes.
CONCLUSIONS

There were a few limitations to the current study. First, a larger sample size may have changed the results and allowed for more comparisons among participants. Second, the participants with PD presented with relatively mild-moderate hypokinetic dysarthria and a more severe group may have exhibited more speech deficits. Also, some participants reported a lack of medication change between the OFF and ON medication states, questioning the effectiveness of medication. Despite these limitations, findings from the current study contribute important information relative to VOT in individuals with PD. Current findings of place of articulation and vowel height effects on VOT correlate with previous studies. Specifically, the VOT ratio and VOT durations (of voiceless sounds) were shortest for bilabials, followed by alveolars. The velar sounds had the longest VOT and VOT ratio values. Examination of vowel height also resulted in confirmation of previous literature, however effects of vowel height were strongest for VOT ratio. The VOT ratios of voiceless sounds were greater for high vowels compared to low vowels.

Contrary to previous research on VOT in PD showing an increase or decrease in VOT, the current study found no significant group effects for PD groups compared to controls. The relatively mildly impaired participants in the current study may have been making articulatory changes to ensure that VOT remained accurate (articulatory undershoot). Therefore, it is probable that individuals who exhibit more severe hypokinetic dysarthria would exhibit more severe VOT deficits, which should be examined thoroughly in future research.

Within the PD group, medication appears to affect VOT in individuals with PD. Because the medication-related changes in VOT were greater than the changes in VOT ratio, it can be
concluded that the changes in VOT were likely the result of medication-related change in word-level articulation rate.

The principal goal of this study was to examine VOT and VOT with the effect of rate removed (VOT Ratio). An interesting dissociation occurred between the two different measures utilized (VOT and VOT ratio). For place of articulation comparisons, VOT and VOT ratio were fairly correlated, showing that rate is not affected by place of articulation changes. However, for vowel height comparisons, significant effects occurred for VOT ratio and not the traditional VOT measure. Rate elimination from VOT was important to examine in these comparisons, confirming that a true VOT difference was found related to vowel height, and that this difference was not the result of an articulation rate change. Because rate was not a dependent measure in the current study, future research should look at altered rate in PD (for example, asking participants to speak faster or slower than their normal rate) to see if there is more or less coupling of rate and VOT for individuals with PD.

To further examine differences between VOT and VOT ratio, medication-related differences in individuals with PD on both measures was calculated. Levodopa appeared to have a greater effect on VOT than VOT ratio, meaning that the difference was actually more reflective of a rate change, rather than a pure VOT change. Overall, the current data support the usefulness of examining both VOT and VOT ratio with individuals with PD, as this method allows for dissociation between rate-related changes and true VOT-related changes in individuals with PD.
REFERENCES


APPENDIX A: INFORMED CONSENT

Voice Onset Time in individuals with Parkinson’s Disease

INFORMED CONSENT

I am being invited to participate in a study of speech production in individuals with Parkinson’s Disease (PD) and other similar-aged participants. This study will be conducted by the Department of Communication Disorders at Bowling Green State University. The purpose of this study is to examine how the voice starts during a variety of speaking tasks. I am ineligible to participate if I am under 18 years old.

**Procedures:** My participation in the study will involve the following: My session will start with filling out a general health questionnaire and possibly some questions about medications relating to PD. After this has been completed, I will be asked to produce a series of speech tasks into a microphone (once before and once after taking my normal morning medication). These will include the production of a series of phrases and paragraphs. The study will take place in the Health Center Building or in a location convenient to me (my home) and the estimated time commitment for each recording is 10-15 minutes.

**Risks:** There are no known risks associated with participation in this study.

**Benefits:** There are no direct benefits to me as a result of my participation in this study. The information will allow researchers to gain a better understanding of speech-medication interactions in those with PD.

**Payment / Costs:** My participation in this study is voluntary. I will receive no payment for my participation. Likewise, there will be no financial cost to me for participating.

**Confidentiality:** All records related to this research will be maintained in a secure area and will be shared only with those assisting with the project. The investigator will not reveal my identity if they publish or present the results of this study.

**Questions:** I have read the information on this form and the investigator has answered my questions. If I have any more questions I can contact Emily Budkowski (740-262-1258) or Alexander Goberman, Ph.D. at BGSU (419-372-2518; goberma@bgsu.edu). If I have questions about the conduct of this study or my rights as a research participant, I may contact the Chair of Bowling Green State University's Human Subjects Review Board at (419) 372-7716 (hsrb@bgsu.edu).

**Consent:** I have been told what will be done in this study. I have also been told how it would be done, what I will have to do, and how long participation will likely take. I am aware that participation in this study is voluntary. I may quit and/or refuse participation at any time without repercussions. If I want it, the investigators will give me a copy of this form to keep for my records.

Subject’s Signature __________________________ Date __________________________

Subject’s Name (print / type)

____________________________

Emily Budkowski
APPENDIX B: INFORMATION/RECORDING SHEETS

Voice Onset Time in individuals with Parkinson’s Disease

INFORMATION SHEET

** Consent form read and signed?**  Yes / No
If no, read / sign the consent form now.

Name: ________________________________

Date of Birth: _______________________

Medical diagnoses:  \( PD \) ________________________________

Approximate age at PD diagnosis: _______________________

Current medications (related to PD): ________________________________

Typical medication times: ________________________________

Typical breakfast time: _______________________

Speech / Language / Hearing History:  Normal / Other : _______________________

History of Smoking:  No / Yes ________________________________

Native speaker of American English:  No / Yes ________________________________

Experiencing fluctuations (before / after medications)?  Yes / No

What times of day are best? ________________________________

What times of day are worst? ________________________________
Voice Onset Time in individuals with Parkinson’s Disease

RECORDING 1 – INFORMATION SHEET

Time of last medication _________________

Time of breakfast _________________

Change in normal routine (i.e., irregular sleep / extra stress / failed dose)?  No / Yes

Time of speech recording:  Start:  _________________  End:  _________________

Right now, how do you rate the following?

<table>
<thead>
<tr>
<th>Parkinsonian symptoms?</th>
<th>Extreme</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>None</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rigidity (tightness)?</td>
<td>Extreme</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>None</td>
</tr>
<tr>
<td>Slowness of movement?</td>
<td>Extreme</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>None</td>
</tr>
<tr>
<td>Difficulty starting movement?</td>
<td>Extreme</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>None</td>
</tr>
<tr>
<td>Tremor (shaking)?</td>
<td>Extreme</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>None</td>
</tr>
<tr>
<td>Speech Symptoms?</td>
<td>Extreme</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>None</td>
</tr>
<tr>
<td>Anxiety?</td>
<td>Extreme</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>None</td>
</tr>
<tr>
<td>How well is your medication working right now?</td>
<td>Not at all</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>Perfectly</td>
</tr>
</tbody>
</table>
Voice Onset Time in individuals with Parkinson’s Disease

RECORDING 2 – INFORMATION SHEET

Time of last medication __________________

Time of breakfast ___________________

Time of speech recording: Start: _____________________ End: _____________________

Right now, how do you rate the following?

<table>
<thead>
<tr>
<th>Parkinsonian symptoms?</th>
<th>Extreme</th>
<th>None</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 2 3 4 5 6 7</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Rigidity (tightness)?</th>
<th>Extreme</th>
<th>None</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 2 3 4 5 6 7</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Slowness of movement?</th>
<th>Extreme</th>
<th>None</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 2 3 4 5 6 7</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Difficulty starting movement?</th>
<th>Extreme</th>
<th>None</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 2 3 4 5 6 7</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tremor (shaking)?</th>
<th>Extreme</th>
<th>None</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 2 3 4 5 6 7</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Speech Symptoms?</th>
<th>Extreme</th>
<th>None</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 2 3 4 5 6 7</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Anxiety?</th>
<th>Extreme</th>
<th>None</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 2 3 4 5 6 7</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>How well is your medication working right now?</th>
<th>Not at all</th>
<th>Perfectly</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 2 3 4 5 6 7</td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX C: DYSARTHRIA ASSESSMENT

Directions and stimuli for the assessment of type and severity of dysarthria:

**Rainbow Passage** (Fairbanks, 1960)

Read the following passage with your normal rate and loudness.

When sunlight strikes raindrops in the air, they act like a prism and form a rainbow. The rainbow is a division of white light into many beautiful colors. These take the shape of a long round arch with its path high above, and its two ends apparently beyond the horizon. There is, according to legend, a boiling pot of gold at one end. People look, but no one ever finds it. When a man looks for something beyond his reach, his friends say that he is looking for the pot of gold at the end of the rainbow.

**Diodochokinetinc rate tasks**

Produce each of the following as fast and steady as possible.

“p^λ-p^λ-p^λ-p^λ …”

“t^λ-t^λ-t^λ-t^λ-t^λ …”

“k^λ-k^λ-k^λ-k^λ-k^λ …”

“p^λ-t^λ-k^λ – p^λ-t^λ-k^λ – p^λ-t^λ-k^λ …”

**Prolonged vowel production**

Produce the vowel “aaaaah” as long and steady as possible on one big breath.

“ahhhhhhhhhhh” (as in hot)
APPENDIX D: STIMULI

Directions and stimuli for Voice Onset Time measurement:
Say these phrases at the normal rate, pitch, and loudness that you would use during everyday conversations.

[t]
teep again
toop again
top again
tap again

[d]
deep again
dupe again
dop again
dap again

[p]
peep again
poop again
pop again
pap again

[b]
beep again
boop again
bop again
bap again

[k]
keep again
koop again
cop again
cap again

[g]
geep again
goop again
go p again
gap again