Speech-Related Sensory Impairment in Parkinson’s Disease

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Yu-Wen Chen

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Abstract

**Background.** Persons with Parkinson’s disease (PD) show speech impairments that are not solely accounted for by motor impairment. In the literature on motor control of trunk and limbs in PD, somatosensory deficits were found and suggested to be associated with movement abnormalities. Less is known about speech-related sensory systems in PD, and little has been done to investigate the link between specific speech sounds and relevant sensory impairments in PD.

**Purpose.** The primary goal of this dissertation is to determine whether there is a relationship between the speech of persons with PD and their auditory and tactile acuity. Using production of sibilants /s/ and /ʃ/ as the speech target, the study seeks to answer four questions: 1) Do persons with PD produce a smaller acoustic difference between sibilant fricatives relative to healthy controls? 2) Do persons with PD show decreased auditory acuity in discriminating spectral shapes? 3) Do persons with PD show decreased acuity to tactile stimuli on the tongue tip? And 4) Are there relationships of sibilant contrast to auditory and lingual-tactile acuity?

**Method.** Ten participants with PD and ten age- and gender-matched healthy participants were studied. Participants performed three tasks. In the production task, they read a passage and eight sentences with /s/- and /ʃ/-initial words; acoustic contrast between the two sibilants was measured using difference between the average first spectral moments of /s/ and /ʃ/. For the auditory task, in each trial they listened to three aperiodic sounds, acoustically modified from /s/ and /ʃ/ and differing in spectral shapes, and judged which sound was different than the other two; auditory acuity measures were calculated from the psychoacoustic functions of their responses. For the tactile task, they judged the orientation of a dome-shaped grating probe gently touching...
their tongue tip; tactile acuity measures were extracted from the psychophysical functions of their responses. Group comparisons were made for every measure and correlation analyses were done between the speech-production measures and sensory acuity measures.

**Results.** Results found that participants with PD had a smaller sibilant contrast than healthy controls for productions in sentences, but not for ones in the continuous speech passage. The PD participants had significantly reduced auditory acuity in discriminating spectral shapes relative to healthy controls, and significantly reduced tactile acuity of the tongue tip. Correlation analyses showed significant correlation between the tactile acuity and sibilant contrast for the PD group.

**Conclusions.** Results from the study suggest associations of sensory impairment to speech production in persons with PD, calling for more research into the sensory underpinnings of the speech problems of this clinical population.
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Chapter 1 Introduction

Parkinson’s disease (PD) is a neurodegenerative disease affecting an estimated one million people in the United States and seven to ten million people worldwide (“Statistics on Parkinson’s - Parkinson’s Disease Foundation (PDF),” n.d.). PD is known to affect both movement and sensory function. Cognitive problems such as difficulty with memory and attention may emerge, especially in the later stages of the disease. Although the disease has been extensively studied, there are questions yet unanswered about it. One of the most intriguing questions regards the underlying mechanisms that result in disordered speech attendant with the disease. Some studies on movement abnormalities of the trunk and limbs in PD have linked the motor symptoms to somatosensory deficits (Konczak et al., 2009). Likewise, it has been hypothesized that persons with PD have a sensory deficit that makes it difficult for them to monitor their speech (e.g., Ramig, Fox, & Sapir, 2011), but empirical evidence for this claim has been scarce. This dissertation investigates the possibility that sensory impairment is one of the underlying mechanisms associated with speech impairment found in PD, specifically the relationship of impaired sensory information on the production of /s/ (as in sad) and /ʃ/ (as in shad) in persons with PD.

1.1 Parkinson’s disease: pathophysiology

Parkinson’s disease affects the basal-ganglia (BG) control circuit. The BG are a collection of intraconnected nuclei located deep in the brain. Components of the BG are the putamen, the
caudate nucleus, the globus pallidus, the subthalamic nuclei, and the substantia nigra. The BG make interconnections with other structures of the brain, comprising the basal-ganglia-thalamo-cortical loop. The putamen and the caudate nucleus are collectively termed the striatum, which is the main area of the BG receiving input from a large area of the cortex. Output of the BG is sent primarily out through the globus pallidus, and is relayed to the thalamus before reaching the cortices. The subthalamic nuclei have reciprocal connections to the globus pallidus. The substantia nigra is divided into two parts: pars reticulata and pars compacta (SNpc). The SNpc contains neurons that manufacture and release the neurotransmitter dopamine via afferent projections to the striatum.

The primary pathology of PD is death of the dopaminergic neurons in the SNpc. With neuronal death, the reduced supply of dopaminergic input to the striatum affects the processing that occurs throughout the BG loop, resulting, in part, to aberrant motor and sensory functions. Sensory signs in PD may include dysfunction of olfaction, vision, somesthesia, and kinesthesia (Chaudhuri, 2011; Konczak et al., 2009). The general motor signs are resting tremor, rigidity, bradykinesia, and difficulty initiating and sustaining movements (Purves et al., 2008). Some specific aberrant motor characteristics may be freezing of movement, shuffling gait, flexed posture, reduced facial expression, decreased blinking, small handwriting (Wichmann & DeLong, 2013) and impaired speech production or dysarthria (Duffy, 2005).

1.2 Speech characteristics of Parkinson’s disease

Many patients with PD have dysarthria. Müller et al. (2001) found that 88% of the postmortem-confirmed cases of PD were previously identified with dysarthria. Parkinsonian dysarthria has been described perceptually and acoustically. This study will use acoustic measures to describe one specific element of speech production. Acoustic characteristics of a speech are the result of cumulative coordination of movement of the speech organs. Acoustic
properties are measurable and reflect the ultimate goal of speech production, i.e., to produce perceptually intelligible speech.

Perceptually, dysarthria associated with PD is described as being soft, monotonous, and articulatorily imprecise. These perceptual characteristics have been supported by acoustic analyses. Reduced vocal intensity, related to soft voice, has been found in speakers with PD (Fox & Ramig, 1997; Ho, Bradshaw, & Iansek, 2000; Sapir, Spielman, Ramig, Story, & Fox, 2007). Reduced variation of prosody, related to monotonicity, was confirmed by studies that found reduced variability of fundamental frequency (Metter & Hanson, 1986; Skodda, Visser, & Schlegel, 2010) and limited fundamental frequency range (Bunton, Kent, Kent, & Duffy, 2001).

Imprecise articulation has been related to atypical acoustics of vowels and consonants. For vowels, studies have found reduced vowel space (Sapir, Ramig, Spielman, & Fox, 2010; Sapir et al., 2007; Skodda, Visser, & Schlegel, 2011) and reduced formant transitions (Forrest, Weismer, & Turner, 1989; Tjaden & Wilding, 2004). Vowel space refers to the Euclidean distance between vowels in the two-dimensional first by second formant frequency (F1 by F2) space. Smaller vowel space leads to a reduction in the distinctiveness of different vowels. Formant transitions are the change of vowel formant frequencies over time between two adjacent sounds, and are an important cue for place of articulation of the consonant sounds flanking the vowels. Reduced vowel space and limited formant transitions have been linked to decrements of speech intelligibility. As one example, Weismer, Jeng, Laures, Kent, and Kent (2001) studied speech in persons with PD and amyotrophic lateral sclerosis (ALS), by measuring several different acoustic variables, including those related to articulation of vowels. Of the acoustic variables studied, reduced vowel space and reduced formant transitions were found significantly correlated to decreased intelligibility in both clinical groups.
For consonants, spirantization of stops was found in parkinsonian dysarthria (Ackermann & Ziegler, 1991; Chenausky, Macauslan, & Goldhor, 2011; Logemann & Fisher, 1981). Spirantization refers to the failure to execute the complete occlusion of the vocal tract. This results in a fricative-like sound when a stop is intended, decreasing the differentiation of stops and fricatives. Furthermore with stop production, studies have identified abnormal voice onset time (VOT, Forrest et al., 1989; Hammer & Barlow, 2010). VOT is the duration from the release of occlusion for a stop consonant to the onset of the following vowel. In normal speech, this measure is longer in voiceless stops than in voiced stops, and serves as an important cue for distinction between the two stop categories. Compared to healthy speakers, speakers with PD demonstrated shorter VOT for the voiceless stop /p/ (Forrest et al., 1989; Hammer & Barlow, 2010) and longer VOT for the voiced stop /b/ (Forrest et al., 1989), resulting in reduced distinction between the two bilabial stops.

Other studies on consonants identified a decreased difference between the first spectral moments (M1D) of /s/ and /ʃ/ in speakers with PD (McRae, Tjaden, & Schoonings, 2002; Tjaden & Wilding, 2004). The first moment (M1), also called the spectral mean or center of gravity, is calculated by treating the power spectrum as a probability-density distribution, and finding the mean of that distribution. M1 of /s/ is located at higher frequencies than that of /ʃ/ and this measure is one of the primary acoustic variables that distinguishes the two sounds (Jongman, Wayland, & Wong, 2000). The difference between the average M1 for /s/ and that for /ʃ/ is referred to as M1 difference (M1D). Decreased M1D has been found correlated to reduced speech intelligibility (Kim, Kent, & Weismer, 2011; Tjaden & Wilding, 2004) and a percept of articulatory imprecision (Tjaden & Turner, 1997) in dysarthrias caused by some neurogenic diseases including PD.
1.3 Sensory-motor links for speech in Parkinson’s disease

As presented in the next chapter, research on motor control of the trunk and limbs has identified somatosensory deficits in persons with PD, and has found, in some cases, that motor impairment of the trunk and limbs were correlated to these somatosensory deficits. However, little is known about whether specific sensory systems believed to be involved in the control of speech are affected in PD and if there is a relationship between these deficits and speech impairment.

This dissertation aims to investigate whether selected speech characteristics in PD are associated with relevant sensory deficits. Chapter 2 of this dissertation is divided into four sections providing necessary background information. The first section will present sensory deficits of the trunk and limbs in PD and their relation to motor impairments. Second, I will briefly discuss how two sensory systems, audition and somatosensation, are involved in speech motor control. Third, I will present what is known of speech-related sensory deficits in PD. Fourth, I will describe research examining relationship of /s/-/ʃ/ production to relevant auditory and somatosensory parameters in healthy speakers, providing a background of using similar experimental approaches to investigate the motor-sensory relationship in the speech of people with PD. The methods, results and general discussion are presented in Chapters 3, 4 and 5.
Chapter 2 Background

2.1 Trunk-and-limb sensory deficits in Parkinson’s disease

Several components of the somatosensory system have been studied in PD relative to movement control of the trunk and limbs. The somatosensory system includes proprioception, exteroception, and interoception (Gardner & Johnson, 2013). Motor control of the trunk and limbs are especially related to proprioception and the sense of touch. Proprioception refers to the sense of oneself, such as posture and movements of our own body. Sense of touch, which is a component of exteroception, includes perception of contact and pressure, and when combined with proprioception, contributes to form haptic sense. Haptic sense refers to the active exploration of objects, and is important for control of movements interacting with our surroundings. These aspects of somatosensation, together with vision, are thought to be critical for movement control.

Findings from four lines of research support links of somatosensory impairments and motor dysfunction in PD. First, studies have found in persons with PD, when visual information is blocked, movements are less accurate, indicating impaired use of somatosensation for motor control (Adamovich, Berkinblit, Hening, Sage, & Poizner, 2001; Klockgether & Dichgans, 1994). For example, Klockgether and Dichgans (1994) designed an experiment where their participants pointed to targets appearing on a tablet, with and without vision of their moving hand and of the target. When participants could not see their hand, and forced to rely on somatosensation, participants with PD would undershoot the target and the movement was slower. The authors
concluded that PD alters sensory feedback from the skin, joint receptors, and muscle spindles, and this alteration is associated with the movement difficulties.

Second, proprioception and haptic sense, both important to movement control of the trunk and limbs, were found impaired in PD (Konczak, Krawczewski, Tuite, & Maschke, 2007; Konczak, Li, Tuite, & Poizner, 2008; Maschke, Gomez, Tuite, & Konczak, 2003; Maschke, Tuite, Krawczewski, Pickett, & Konczak, 2006), and in a few reports, direct correlations between the sensory impairments to motor symptoms were observed. With regard to haptic sense, Maschke et al. (2006) studied participants’ perception of heaviness by applying increasing amounts of force to participants’ index finger until they detected the application of weight. Participants with PD showed elevated detection thresholds, demonstrating decreased sensitivity to heaviness. The authors reported a trend ($r = 0.55, p = 0.09$; sample size = 10) that their PD group’s scores of the motor section of the Unified Parkinson’s Disease Rating Scale (UPDRS-Motor) were positively correlated with weight-perception thresholds, indicating association of decreased haptic sensitivity (i.e., increased detection threshold) to motor symptoms.

For impaired proprioception, Maschke et al. (2003) investigated perception of passive displacement of the forearm. Participants were tested on a passive motion apparatus, where their forearm rested on a padded splint that could flex or extend the forearm in various degrees of displacements. For each trial, participants’ forearm was moved for a small angle with vision occluded, and participants judged whether their forearm had been moved ‘towards’ (flexion) or ‘away from’ (extension) their body. Results showed that participants with PD were less accurate in the judgment, indicating a reduced acuity in elbow-joint position sense. Further, the correct response rates were significantly negatively correlated with their UPDRS Total scores ($r = -0.7, p = 0.03$). Konczak et al. (2007) also conducted a study on passive motion detection on the forearm. Unlike Maschke and colleagues’ (2003) setup, in Konczak et al. (2007), the movements in each trial persisted until participants pressed a button to indicate they detected a movement.
After motor response time was adjusted for, participants with PD were found to require larger degrees of displacement to detect the movement, suggesting a decreased sensitivity to passive motion. A positive correlation between UPDRS-Motor scores and displacement-detection angles was reported ($r = 0.56, p < 0.01$).

Third, impaired proprioceptive guidance during voluntary movements has been observed in persons with PD. In two studies, proprioceptive feedback was manipulated by applying vibration to participants’ antagonist muscles (Khudados, Cody, & O’Boyle, 1999; Rickards & Cody, 1997) during voluntary movements. In neurologically healthy participants, this manipulation would cause them to undershoot their movements. Rickards and Cody (1997) applied the vibration to their participants’ tendon of the flexor carpi radialis when participants performed voluntary wrist-extension movement; and Khudados et al. (1999) stimulated the antagonist muscle spindles by vibrating the Achilles tendon while participants performed voluntary dorsiflexion movement of the ankle joint. In both studies, the vibration induced undershooting errors in participants with and without PD, but participants with PD made smaller undershooting errors compared to healthy controls. The findings indicate that PD altered the proprioceptive guidance during voluntary movements.

Fourth, motor improvements were found after persons with PD underwent proprioceptive rehabilitation. Proprioceptive training refers to exercises focused on improving specific components directly related to proprioception itself or the integration of proprioceptive signals (Abbruzzese, Trompetto, Mori, & Pelosin, 2014). Some approaches, including augmented feedback (Bieńkiewicz, Rodger, Young, & Craig, 2013; Byblow, Lewis, & Stinear, 2003; del Olmo, Arias, Furio, Pozo, & Cudeiro, 2006) and focal vibration (De Nunzio, Grasso, Nardone, Godi, & Schieppati, 2010; Novak & Novak, 2006), applied on persons with PD were shown to improve upper- and lower-limb motor functions. For example, with synchronized vibration to the
foot soles, locomotion parameters such as stride variability, walking speed, stride duration, stride length and cadence were improved in persons with PD (Novak & Novak, 2006).

Contrasted to those related to movement control of the trunk and limbs, sensory deficits related to speech in PD are less well known. In the next sections, I will discuss sensory systems associated with speech production, and then present evidence that these senses may be impaired in PD.

2.2 Sensory systems associated with speech production

This section discusses the senses believed most important for speech production, i.e., audition and somatosensation (Hickok, 2012; Houde & Nagarajan, 2011; Perkell, 2012; Tourville & Guenther, 2011). First, I will present an abbreviated overview of a model of speech production, demonstrating how sensory inputs are used in speech motor control. Within this section, I will present evidence supporting the involvement of audition and somatosensation in the learning, control, and maintenance of normal speech production.

2.2.1 Roles of the sensory inputs in speech production: an overview

A simplified overview of speech motor control is shown in Figure 2-1. To produce speech, the cortical controller incorporates inputs from the sensory systems regarding the state of the articulators and the environment to generate motor commands. This process is called motor planning. A motor command is then sent from the cortical controller to relevant muscular structures to produce speech, which results in associated sensory feedback. At the same time, an efference copy of the motor command is sent to the internal model, which transforms this efference copy to an expected sensory outcome. The expected sensory outcome is compared with the actual sensory feedback. The result of the comparison is sent back to the cortical controller and can be used for future motor planning.
Motor plans and internal models, together referred to as the feedforward mechanism, are acquired during the acquisition stage of speech development. At this stage, sensory inputs are used to develop associations between motor commands and expected sensory feedback. During motor planning, specific motor commands can be generated according to what the desired speech outcomes are. Once the feedforward mechanism is developed, speech production is largely guided by it, while sensory inputs serve to monitor and maintain speech production and, when necessary, modify the feedforward mechanism. The maintenance and modification of the feedforward mechanism relies on comparisons between sensory feedback and the expected sensory outcome. After a speech element is produced, if a comparison yields no discernable
mismatch, the internal model and motor command are maintained. If there is a mismatch, however, the motor system incorporates the mismatch into future motor planning so that the subsequent motor commands are adjusted. And if the mismatch persists, the motor command and associated internal model may be recalibrated. Because of the maintenance and modification processes, when sensory inputs are impaired or not available during speech production, over the long term, feedforward mechanisms are no longer well maintained and may deviate from normality.

In the next two sections, I will discuss the importance of audition and somatosensation to speech. I will first discuss evidence showing speech abnormalities that occur with sensory deprivation, and second how modifying sensory feedback can affect normal speech production.

2.2.2 The importance of auditory input to speech production

The importance of auditory input in acquiring speech is best demonstrated by children without normal hearing during the speech acquisition stage, such as prelingually or congenitally deafened children. For these children, speech acquisition is significantly impaired and requires years of special training for them to learn to produce intelligible speech (Mogford, 1988).

After speech is acquired, auditory feedback is used to monitor speech, and ongoing auditory input helps maintain normal speech production. If auditory information becomes unavailable, such as in persons with postlingual deafness, speech can still be normal for a period of time (Cowie, Douglas-Cowie, & Kerr, 1982), but intelligibility and articulatory precision deteriorate over time (Lane & Webster, 1991; Plant, 1984; Waldstein, 1990). For example, Lane and Webster (1991) found several acoustic differences of speech in three postlingually deafened speakers a relatively short period of time (1.5, 1.5, and 6 years) after the onset of deafness. These included differences in a variety of sounds, including both vowels and consonants. They measured coefficients of variation in F0 of vowels (a measure of trial-to-trial stability of
production), M1D of /s/ and /ʃ/ (a measure of how robustly different /s/ and /ʃ/ are produced), and spectral slopes for the stop consonants (a measure of the precision with which the consonants are produced). Compared to three age- and gender-matched normal hearing speakers, coefficient of variation in F0 was significantly larger in the deaf speakers, indicating a more variable pitch in their speech. The deaf speakers showed significantly reduced M1D compared to the normal hearing speakers, indicating a reduced contrast between the two sounds. Spectral slopes are used to distinguish place of articulation in stop consonants; in typical productions of stops, spectral slope increases as place of articulation moves toward the back of the oral cavity. Lane and Webster (1991) found that their deaf speakers showed similar spectral slopes for the bilabial stops /p, b/ and the alveolar stops /t, d/, demonstrating a reduction in these speech sound contrasts. Their study demonstrated that after as little as 1.5 years following the onset of deafness speech output had changed.

The importance of auditory feedback for monitoring and maintaining speech production has also been verified by studies on sensorimotor adaptation. In these studies, healthy speakers vocalized speech and listened to real-time auditory feedback through headphones. Researchers perturbed the auditory feedback by modifying the acoustic parameters of intensity (Bauer, Mittal, Larson, & Hain, 2006), fundamental frequency (Burnett, Senner, & Larson, 1997), vowel formant frequencies (Houde & Jordan, 1998; MacDonald, Goldberg, & Munhall, 2010; MacDonald, Purcell, & Munhall, 2011; Purcell & Munhall, 2006; Villacorta, Perkell, & Guenther, 2007), and the spectral properties of /s/ (Shiller, Sato, Gracco, & Baum, 2009), so that the feedback speakers received did not match the expectations generated by their internal models. In general, these studies found that, under auditory feedback perturbation, speakers often changed their vocal production to compensate for the mismatch. Most speakers did so by opposing the perturbation. For example, when Schiller and colleagues’ participants produced words beginning with /s/ and
/ʃ/, while the M1 of /s/ was lowered by approximately 1430 Hz, making the /s/ sound closer to /ʃ/, they responded by increasing the M1 of /s/.

Interestingly, these studies found the amount of compensation varied from speaker to speaker, with an average of about 30% of the perturbation magnitude. For example, in Shiller and colleagues’ (2009) study mentioned above, their participants increased their M1 an average of 529 Hz, with a standard error approximately 120 Hz. The standard error suggests that speakers differed widely in how much articulatory change they made when faced with the auditory mismatch. Subsequent studies were done to look into the reasons for the variation in compensation magnitude. Villacorta et al. (2007) posited an association between compensation magnitude and auditory perceptual acuity. They designed two tasks to test their hypothesis that for speakers more acute in discriminating a certain acoustic variable, they are more likely to make larger compensatory changes in order to eliminate or minimize the auditory mismatch when its feedback is perturbed. For their perturbation task, the authors shifted participants’ first formant frequencies up or down, causing the vowel /ɛ/ to sound more like /æ/ or /ɪ/, respectively. Their results were similar to findings from other adaptation studies; participants compensated for the perturbation, and the magnitudes of the responses varied among participants. Next, participants performed a discrimination task, in which they listened to pairs of monosyllabic words and judged whether they were the same or different. Words in each pair were either identical or the vowels were different in varying degrees of the first formant frequency. Results showed a significant positive correlation between auditory acuity and the magnitude of the adaptive response. As will be discussed later, such a relationship between sensory acuity and speech production was also found in /s/ and /ʃ/ (Ghosh et al., 2010; Perkell et al., 2004).
2.2.3 The importance of somatosensory input to speech production

Similar to what happens when auditory feedback is unavailable, deprivation and perturbation of somatosensory feedback of the articulators has been shown to affect speech. Studies using nerve block and mechanical perturbation have provided insight regarding the importance of somatosensory input for the control of speech. In a series of studies, Niemi and colleagues (Niemi et al., 2002; Niemi, Laaksonen, Aaltonen, & Happonen, 2004; Niemi, Laaksonen, Ojala, Aaltonen, & Happonen, 2006) found that speech was affected when speakers’ tongues were anaesthetized by lingual nerve injection, blocking somatosensory input from the tongue. Although findings were highly variable between speakers, acoustic parameters of vowels, diphthongs, and the consonant /s/ changed in most speakers after nerve blocking. For example, Niemi et al. (2006) examined spectral properties (M1, standard deviation, skewness, and kurtosis) of /s/ before and after nerve blocking. Out of their five speakers, significant changes in spectral measures were found in four speakers: in three of them M1 decreased and in one it increased.

Studies on sensorimotor adaptation confirmed that somatosensory input is used to monitor speech and to update the feedforward mechanisms. These studies changed participants’ vocal-tract shape using articulator prostheses (Baum & McFarland, 1997; Lindblom, Lubker, & Gay, 1979; McFarland & Baum, 1995; McFarland, Baum, & Chabot, 1996; Savariaux, Perrier, Orliaguet, & Schwartz, 1999) or perturbed the articulatory trajectory by applying external forces with robotic devices (Nasir & Ostry, 2006, 2008; Tremblay, Houle, & Ostry, 2008; Tremblay, Shiller, & Ostry, 2003). Participants’ responses were described by acoustic measures of their speech or by movements or trajectories of their articulators.

Lindblom et al. (1979) measured formant frequencies when speakers produced the Swedish vowels /i, u, o, ɑ/ with and without a bite block placed between their lateral incisors. This
manipulation induced a larger-than-normal jaw opening during speech. In spite of the presence of the bite block, the formant frequencies fell within the range of normal speech, indicating that speakers successfully compensated for the perturbation to jaw position. In Baum and McFarland (1997), participants’ vocal tract was changed by an artificial palate attached to the upper alveolar ridge, creating a six-mm ridge that modified the distance of the tongue to the palate. This perturbation affected the production of /s/, which requires raising the tongue blade toward the alveolar ridge to create a narrow passage for the air stream to pass through. With the artificial palate in place the passage becomes even narrower if the participants do not adjust the position of their tongue blade. Participants repeated the syllable /sɑ/ 30 times with the artificial palate in place at five time intervals (T0, T15, T30, T45 and T60) with 15 minutes apart. Between each interval they read /s/ laden paragraphs for 15 minutes with the artificial palate in place. M1 was measured to quantify the production of /s/. Before application of the artificial palate, average M1 from the syllable repetitions was 8091 Hz. With the artificial palate, at T0, average M1 value was 6989 Hz. Over time, M1 values approached pre-prosthesis production: at T45 and T60, they were 7653 Hz and 7587 Hz, respectively. The improvement of M1 values over time indicates that participants adapted to the presence of the artificial palate.

The other line of sensorimotor-adaptation research employed dynamic mechanical perturbation by applying an external force to the articulators during movement to create abnormal trajectories of the articulators during speech (Nasir & Ostry, 2006, 2008; Tremblay et al., 2008, 2003). One such example by Tremblay et al. (2003) attached a robotic arm to participants’ lower incisors to apply a force orthogonal to the jaw opening direction, pulling their mandible forward during production of the pseudo word /siæs/. Participants’ lower-lip locations (used to track jaw movement) were recorded in the sagittal plane and the paths were drawn using a two-dimension coordinate, with jaw protrusion on the abscissa and jaw height on the ordinate (See Figure 2-2). Participants said the pseudo word in three phases: in baseline without perturbation for 20 trials, in
the training phase with perturbation for 525 trials, and after training without perturbation for 30 trials. Jaw trajectories were measured and averaged for four sets of trials: the baseline curve averaged from the baseline trials (shown as the black curve in Figure 2-a), the initial-exposure curve averaged from the first 105 trials of the training phase (shown in blue), the end-of-training curve averaged from the end 105 trials of the training phase (shown in red), and the after-effect curve from the after-training trials where perturbation was removed (shown in green). As can be seen in Figure 2-a, at baseline when the jaw moved from closing of /i/ to opening of /æ/ the trajectories involved a slight curve going downward. When the perturbing force was first applied, the trajectories showed an increase of curvature, indicating the effects of the external force protruding the jaw. After exposure to the force, the curvature reduced and the trajectories matched those at the baseline, indicating that participants learned to oppose this force when producing the target word. Further, this adaptation was retained after the training phase, when the external force was removed there was indication of an after-effect of motor learning (shown in green in Figure 2-a).

Because changing articulator trajectory (e.g., Tremblay et al., 2003) or shapes of the vocal tract (e.g., Baum & McFarland, 1997) also changed the acoustic outcome, adaptation could have been driven by a auditory rather than a somatosensory mismatch. In order to test this phenomenon and also to test whether the adaptive behavior is generalized to non-speech motor control, in the same study, Tremblay et al. (2003) recruited two other groups of participants to perform the same procedure but under different conditions. Instead of vocalizing speech, one group was instructed to produce the syllable in silence and another group was instructed to repeat non-speech jaw-opening and -closing movements. The results are shown in Figure 2-b and Figure 2-c, respectively. As can be seen in the figures, without auditory feedback, speakers still adapted to the external force and showed after-effects, but neither adaptation nor after-effects were seen in the non-speech movements. This indicates that at least part of speech production
depends on somatosensory feedback, and that somatosensory perturbation can induce adaptation in order to produce desired articulator trajectories. This adaptation, however, is specific to speech-related jaw movement.

Figure 2-2 Speakers showed adaptation to external force applied to the jaw (Tremblay et al., 2003). Colored curves show trajectories from different trials throughout the experiment. Black curves show trajectories of the baseline trials, blue curves show trajectories of the initial 105 trials when external force was first applied, red curves show trajectories of the end 105 trials with external force on, and green curves show trajectories of the trials during the after-effect phase, after the external force was removed.

In summary, speakers’ responses to articulatory perturbation demonstrated the importance of somatosensory feedback to speech production. When there is a mismatch between predicted somatosensory outcome and perceived somatosensory feedback, speakers adjust their articulation in order to minimize the mismatch. These findings indicate that in addition to audition, somatosensation also plays a role in the control of speech production.
2.3 Speech-related sensory deficits in Parkinson’s disease

Because sensory inputs are used to monitor and maintain typical speech production, a person’s speech is subject to change if this sensory guidance is altered. It is an emerging idea that sensory deficits can underlie speech characteristics in PD. For example, when discussing voice and speech of PD, Ramig et al. (2011) suggested sensory abnormalities be important factors in speech and voice characteristics in PD. Although not explicitly stated, the most commonly administered voice-speech treatment program, the Lee Silverman Voice Treatment (LSVT), also demonstrates a sensory-based approach. By teaching and training the patients to re-learn the relationship between the speech outputting parameters and perceived sensory feedback, the LSVT program has reported many successful treatment effects (e.g., Fox et al., 2006). However, up to date, very little empirical evidence exists supporting this sensory-speech relationship or impairment in speech-related sensory systems in PD. In this section, I will present this emerging but small set of data demonstrating impairment in both speech-related audition and speech-related somatosensation in persons with PD.

2.3.1 Auditory deficits found in persons with Parkinson’s disease

Investigation of speech-related auditory perception in persons with PD initially identified abnormal auditory temporal processing and disordered perception of emotional and grammatical prosody (See Kwan & Whitehill, 2011 for a review). However, perception of emotional and grammatical prosody involves cognition and attention, which may be impaired in PD, making it difficult to draw conclusions from these earlier studies as to whether there was a deficit in auditory processing. The findings from studies in temporal processing in PD have not been consistent. Some studies have found deficits in the processing of auditory stimuli of short durations only (Rammsayer & Classen, 1997; Riesen & Schnider, 2001) and others show auditory
temporal processing deficits of only long time spans (Smith, Harper, Gittings, & Abernethy, 2007).

A few studies have employed methods that are closer to reliable psychoacoustic approaches, to minimize possible confounds. Abnormal perception of vocal loudness was first systematically studied in persons with PD by Ho et al. (2000). Ho and colleagues chose to study loudness perception because it is believed to be one of the main variables affected in parkinsonian speech. In their study, participants with and without PD, all of whom passed a hearing screening, were recorded reading the Rainbow Passage. Next, participants listened to their own recordings, and were instructed to turn a knob on an amplifier to match how loud they thought they originally read the passage. Ho and colleagues found that although their participants with PD spoke with reduced intensity, they adjusted their recordings to a greater intensity than the healthy-control group did. The results indicate participants with PD overestimated their own volume, suggesting a relation between disordered voice intensity and abnormal auditory perception of vocal loudness.

More recently, Clark, Adams, Dykstra, Moodie, and Jog (2014) found their participants with PD who also had hypophonia (lower-than-normal vocal intensity) showed a different function in loudness estimation than their matched healthy controls. The two groups of participants scaled the loudness of a sentence presented to them at five intensity levels (60, 65, 70, 75, and 80 dB). A magnitude estimation method was used to elicit loudness scaling. The sentence presented at 70 dB was used as the modulus and was assigned the number 100, and participants gave numbers relative to 100 to indicate how loud they perceived the sentence presented in the other intensity levels. When the sentence was presented at lower intensities (60 and 65 dB), participants with PD gave larger numbers than the controls, indicating an overestimation of loudness at this intensity range. But when the sentence was presented in higher intensities (75 and 80 dB), participants with PD gave smaller numbers than the controls,
indicating they underestimated the loudness. The authors suggested that PD is associated with impairment in perceiving externally generated loudness.

In three psychoacoustic tasks, Troche, Troche, Berkowitz, Grossman, and Reilly (2012) had participants discriminate pure-tone pairs manipulated in one of three parameters: amplitude (related to loudness perception), frequency (related to pitch perception), and duration. For each of the three parameters, tone pairs in a trial were either the same or of a small or large difference. The difference was either 6 dB or 12 dB for amplitude trials, 25 Hz or 100 Hz for frequency trials, and 500 ms or 2000 ms for duration trials. Participants indicated whether each pair was the same or different. The results showed that the participants with PD were less accurate in discriminating tone pairs with smaller differences of amplitude and frequency, but they were as accurate as controls in discriminating the duration of tone pairs.

Findings from studies using auditory adaptation paradigm provide further support of auditory perceptual impairments, including pitch and loudness, in persons with PD. In studies that shifted fundamental frequency in real time, speakers with PD showed larger-than-normal compensation magnitude (Chen et al., 2013; Liu, Wang, Metman, & Larson, 2012). For loudness, Liu et al., (2012) had their speakers prolong /ɑ/, while the loudness in the auditory feedback was shifted upward (louder) or downward (softer) by 3 dB or 6 dB. Compared to the controls, their participants with PD showed larger response magnitudes for both shift-directions and both shift-magnitudes.

In summary, persons with PD demonstrate differences in making judgments of auditory stimuli and also show a different pattern of adaptation to auditory feedback perturbation. These findings together suggest that PD is associated with an auditory impairment related to voice and speech.
2.3.2 Somatosensory deficits found in persons with Parkinson’s disease

Somatosensory impairment in the articulatory structures has been found in PD patients. Schneider, Diamond, and Markham (1986) examined orofacial somatosensation, including jaw proprioception and tactile perception of the teeth, gums, lips, and tongue. For jaw proprioception, the authors inserted a caliper with dental bite plates into the participants’ mouth. The caliper either opened or closed participants’ jaw, and participants indicated their perceived jaw position by pointing their fingers up or down. The participants with PD were less accurate in discriminating whether the caliper opened or closed the jaw, indicating proprioceptive deficits in the jaw. For tactile perception, participants with PD were found less accurate in localization of tactile stimuli on the gums, lips, and tongues, tested in separate tasks. A two-point discrimination task on the upper lip also found elevated thresholds in participants with PD.

Somatosensory impairments have also been found in the larynx in persons with PD. To test the sensitivity of laryngeal mechanoreceptors, Hammer and Barlow (2010) applied airbursts produced by different amounts of pressure to participants’ laryngeal mucosa. Participants pressed a hand-held switch to indicate detection of the stimulus. Laryngeal mechanosensory detection threshold was calculated for every participant. Results found that participants with PD required significantly larger pressure to detect the airburst compared to the healthy-control group, indicating a decreased sensitivity to air pressure.

One very important finding of Hammer and Barlow’s (2010) study concerns associations between sensory deficits and relevant speech parameters. In a speech production task, their participants repeated the syllable /pɑ/, from which several acoustic and aerodynamic measures were taken. Examination of aeromechanical variables found that participants with PD had lower tracheal air pressure, reduced peak airflow, reduced laryngeal resistance, and reduced lung volume expenditure for each syllable spoken. Acoustic measures revealed reduced intensity and
shorter VOT in the PD patients. For the PD group, correlation analyses revealed that the aeromechanical and acoustic measures listed above were significantly negatively correlated with the laryngeal mechanosensory detection threshold. The significance of this finding is that, for the first time to my knowledge, it demonstrated a relationship between somatosensory deficits and relevant speech production variables in PD.

2.4 /s/-/ʃ/ production: A window into understanding the relationship between speech production and sensory acuity in Parkinson’s disease

As discussed in the first chapter, acoustic studies in PD have found abnormalities in both the production of vowels and consonants. Acoustic contrast between similar consonants such as /s/ and /ʃ/ is known to be reduced in PD (McRae et al., 2002; Tjaden & Wilding, 2004). Production of these two sounds is dependent upon both somatosensory and auditory feedback (Perkell, 2012; Perkell et al., 2004). Thus, studying production of these sounds and the relevant sensory systems may provide further opportunity to understand the sensory-motor link in parkinsonian speech.

2.4.1 Production of /s/ and /ʃ/: significance of audition and tactile sense in normal speakers

Consonants are typically described by manner and place of articulation. Manner of articulation refers to how the constriction of the vocal tract is formed between articulators to produce the consonant. For example, a complete constriction is required when producing a stop, and a narrow but not complete constriction is required for fricatives. Within the English fricatives, /s/ and /ʃ/ are also called sibilants because of their high-pitched hissing and hushing sound quality. Place of articulation describes where the constriction is formed along the vocal
tract. The two sibilants /s/ and /ʃ/ are produced with similar degrees of constriction (therefore the same manner of articulation), but they differ in place of constriction, which determines the acoustic and subsequent perceptual features.

Excerpted from Perkell (2012), Figure 2-3 illustrates articulation and acoustic consequences of /s/ and /ʃ/. Production of these two sounds requires formation of a narrow constriction in two different locations in the anterior oral cavity. The constriction is formed by raising the tongue blade toward the roof of the oral cavity (Figure 2-3B), so that the expiratory airstream passing through this constricted area creates a turbulent air jet, resulting in aperiodic noise. These two sibilants differ in their place of constriction. Production of /ʃ/ involves raising the tongue blade toward the anterior portion of the hard palate, forming a narrow passage between the tongue and the palato-alveolar area (Figure 2-3B, left). Production of /s/ requires raising the tongue blade toward the alveolar ridge, a more anterior placement, to form a narrow passage between the tongue and the dento-alveolar area (Figure 2-3B, right).

Acoustically, this difference in placement of constriction results in different energy distribution along the spectra for the two sibilants. This energy distribution is usually measured by M1, also called center of gravity or the spectral mean, which is the frequency at which the spectral energy is divided into two equal halves. Treating a spectrum as a histogram, the M1 is the median frequency. For /ʃ/, M1 is located in the frequency range around 4 kHz, while for /s/ M1 is above 6 kHz (Figure 2-3A). Contrast between these two sibilants is usually measured by the difference between their M1 values, conventionally referred to as M1D.
Figure 2-3 A: Spectra for /ʃ/ (left) and /s/ (right). B: Diagram of tongue positions required for production of /ʃ/ (left) and /s/ (right). C: A curve showing volume of sublingual cavity when producing /ʃ/ and /s/ (Perkell, 2012).

Perkell et al. (2004) noted that the more retracted tongue position of /ʃ/ establishes a sublingual cavity between the ventral side of the tongue blade and the back of the lower incisors (Figure 2-3B, left), while during production of /s/ this sublingual cavity does not exist (Figure 2-3B, right). As the tongue moves forward from placement of /ʃ/ toward placement of /s/, volume of the sublingual cavity reduces until it drops to zero when the tongue tip touches the lower incisors for production of /s/ (Figure 2-3C).

Perkell and colleagues (2004) hypothesized that the somatosensory goal of /s/ is to eliminate this sublingual cavity, by raising and advancing the tongue blade forward toward the upper alveolar ridge so that the tongue tip makes contact with the lower incisors and alveolar ridge. Therefore, a speaker’s articulatory contrast between /s/ and /ʃ/ may be related to whether he or she makes the contact when producing the two sounds. The authors investigated this hypothesis by measuring how often this contact was made during their participants’ /s/ and /ʃ/
production. To detect whether there was a contact, a sensor, triggered by the frication noise, was attached to the participants’ lower incisors and alveolar ridge. If the sensor detected a contact during production of the sibilants, a score of one was assigned; if the sensor did not detect a contact, a zero was assigned. The proportion of contacts made for each sibilant was calculated, and contact difference was computed by subtracting the proportion of contacts for /ʃ/ from that of /s/. Participants were then divided into two groups based on contact difference: those with greater contact differences as the high-contact group and those with lesser contact differences as low-contact group. M1D from the participants’ production of /s/ and /ʃ/ was calculated as the measure of /s/-/ʃ/ contrast. Group comparison revealed significantly larger M1D for the high-contact group than the low-contact group, supporting the authors’ hypothesis for articulatory goal that production of /s/ involves a contact of the tongue tip and the lower incisors while production of /ʃ/ does not. These findings indicated that somatosensation, or specifically, tactile perception of the tongue tip might be important to articulating the contrast between /s/ and /ʃ/. This suggestion was later confirmed by Ghosh et al. (2010), to be described subsequently.

Because the acoustic contrast between /s/ and /ʃ/ lies in spectral shapes, auditory acuity in perceiving frequencies of noise energy distribution related to the two sibilants is assumed important for their production. In the same study described above (Perkell et al., 2004), auditory acuity in perceiving spectral differences was tested using a discrimination task. The stimuli were a series of quasi-sibilant noises created by modifying the M1 along the /s/-/ʃ/ continua. In each trial, participants listened to three of these sounds from the same continuum in an ABX paradigm, where sounds A and B differed by one, two, or three steps, and X was the same with either A or B. Participants responded with whether the third sound was the same as the first or the second. Proportion of correct discrimination was then calculated for the participants, who were divided into two groups based on whether they had high or low auditory acuity. Group-comparison for
M1D showed that participants in the high-auditory-acuity group produced greater /s/-ʃ/ contrast (larger M1D) than those in the low-auditory-acuity group. The authors further performed a simple cross-participant correlation analysis and found a significant positive correlation between proportion correct for the auditory discrimination and M1D for /s/-ʃ/ production, indicating the more acute a participant was in discriminating spectral shapes of the noises, the better they produced /s/-ʃ/ contrast. In summary, Perkell et al. (2004) showed a relationship between speech production of /s/-ʃ/ contrast and auditory acuity in discriminating spectral shapes in healthy speakers. Their findings also suggested that tactile acuity of the tongue tip might be important in the distinct production of the two sounds.

The relationship between sensory acuity and production contrast between /s/ and ʃ/ was further investigated in Ghosh et al. (2010). The spectral moments (M1, skewness and kurtosis) of their participants’ production of /s/ and ʃ/ were measured and acoustic contrast distances were calculated from these moments. For sensory acuity, the authors tested participants’ tactile acuity of the tongue tip and also auditory acuity of spectral shapes. The participants’ tactile acuity was tested using the JVP Domes™, consisting of eight small dome-shaped probes with equal-distant gratings on the domed surface, used to test tactile spatial acuity on body surfaces. The eight domes in the system differ in grating resolution, with groove width from 0.35 mm to 3.00 mm. When the grating surfaces of these domes were pressed against participants’ tongue tips, participants were to respond with what orientation the gratings were (vertical, horizontal, or diagonal). To measure tactile acuity, the authors identified participants’ maximum correct response rate for each grating resolution. A correlation analysis found a significant positive correlation between the acoustic contrast distance from the speech production task and the maximum correct response rate from the tactile task, indicating that participants with higher tactile acuity of the tongue tip produced better /s/-ʃ/ contrast.
Auditory acuity was further investigated by Ghosh et al. (2010) using a discrimination task with an adaptive paradigm. The stimuli consisted of 841 steps along a /s/-ʃ continuum created by modifying frequencies of the spectral peaks, resulting in varying M1 values. A four-interval two-alternative forced-choice paradigm was used in which participants listened to sequences of stimuli in the form of A-B-A-A or A-A-B-A, and responded whether the second or the third stimulus was different from the rest. An adaptive procedure was used to search for auditory just-noticeable difference (JND) in M1 for each participant. As a result, a significant negative correlation was found between acoustic contrast distance and auditory JND, indicating that speakers with more acute auditory discrimination to spectral shapes also spoke with larger acoustic contrast between /s/ and /ʃ/.

2.4.2 A summary: investigating the speech-sensory relationship in /s/-ʃ helps further our understanding about Parkinson’s speech

There are several reasons why investigating /s/ and /ʃ/ in speakers with PD can provide a possible window into examining the relationship between speech production and sensory deficits in this population. First, the relationships between sensory acuity and goodness of /s/-ʃ contrast have been documented in neurologically healthy speakers, as discussed in 2.4.1. Second, production of /s/ and /ʃ/ was found impaired in PD, as discussed in 1.2. Third, research findings support the existence of auditory and somatosensory deficits in persons with PD, as discussed in 2.3. This raises the question as to whether there is a link between the speech impairment and sensory deficits in persons with PD in relation to the production of /s/ and /ʃ/? Understanding the important link will further our knowledge about parkinsonian speech. And studying the production of /s/ and /ʃ/ and relevant sensory acuity is one way to explore this link.
Adapting the methods of Perkell et al. (2004) and Ghosh et al. (2010), this dissertation study examines the relationship between the spoken /s/-/ʃ/ contrast and relevant sensory acuity, i.e., auditory acuity in discriminating spectral shapes of the two sibilants, and tactile acuity of the tongue tip, in persons with PD. The research questions are:

1. Is /s/-/ʃ/ spectral contrast reduced in speech of persons with PD?
2. Is auditory acuity in discriminating spectral shapes of /s/ and /ʃ/ reduced in persons with PD?
3. Is tactile acuity of the tongue tip reduced in persons with PD?
4. Is there a relationship between /s/-/ʃ/ contrast and sensory acuity in persons with PD?

To answer the first question, M1D of participants’ /s/ and /ʃ/ will be measured and compared between participants with and without PD. To answer Question 2, participants will perform an auditory-perceptual task that probes their ability to discriminate noises differing in spectral shapes. Their auditory discrimination acuity will be quantified using two measures identified from the psychoacoustic function curves generated based on their responses, and group comparisons will be made of both measures. The first measure is the just-noticeable-difference threshold (JND_{AUD}) at which a person discriminates the stimuli better than chance. The other measure, area of uncertainty (AOU_{AUD}), indicates how certain a person is around their JND. These two measures are further described and defined in Chapter 3. The subscript _AUD is used to specify the measures for auditory perception. To answer Question 3, participants will perform a tactile-perceptual task that probes their ability to discriminate grating orientations at their tongue tip. Similar to the auditory acuity task, tactile discrimination acuity will be quantified using two measures (JND_{TAC} and AOU_{TAC}) identified from the psychophysical function curves of participants’ responses, and group comparisons will be made of them. To answer the fourth
question, correlation analyses will be done for the sensory acuity measures and M1D values for the two groups.

The hypotheses are:

1. Participants with PD will produce smaller /s/-/ʃ/ M1D when speaking.
2. Participants with PD will show reduced auditory acuity, demonstrated by elevated $JN_{AUD}$ and enlarged $AOU_{AUD}$.
3. Participants with PD will show reduced tactile acuity, demonstrated by elevated $JN_{TAC}$ and enlarged $AOU_{TAC}$.
4. There will be negative correlations in both groups
   a. between M1D and auditory acuity measures, and
   b. between M1D and tactile acuity measures
Chapter 3 Method

3.1 Participants

Two groups of participants were studied: one with idiopathic Parkinson’s disease (PD) and one with neurologically healthy controls (HC). There were 5 men and 5 women in each group. Participants in the HC group were gender- and age-matched (±5 years) to individuals in the PD group. Table 3-1 shows the description of participants with PD. At the time of testing, mean age for the PD group was 63.7 (SD = 3.97; Range 54-69) and that of the HC group was 63.9 years old (SD = 4.23; Range 57-73). A two-sample t-test found no difference in age between the two groups (p = 0.91).

To meet criterion for participation, each group member had to have North-American English as his or her native language. Participants with PD self-reported that they were diagnosed with idiopathic Parkinson’s disease, had no other neurological disorder including dementia, and had no history of speech, language or hearing disorders other than those associated with PD. None of the PD participants had received any surgery as a treatment for their PD.

Disease duration of participants with PD ranged between 1 year and 12 years, 3 months. Nine of them were on anti-parkinsonian medication. Participants with PD also filled out self-rating forms to report disease stage and severity of symptoms. Disease stage was reported using the Hoehn and Yahr Scale (Hoehn & Yahr, 1967), for when they felt at their best and when they felt at their worst. According to their reports, disease stages ranged between 1 and 4 (see Table 3-1). Severity of specific symptoms was self-rated using the Activity of Daily Life questionnaire
from the United Parkinson’s Disease Rating Scale (UPDRS-ADL; Fahn, Elton, & Members of
the UPDRS Development Committee, 1987). UPDRS-ADL scores obtained at time of the
experiment ranged between 3 and 12 out of 52, with an average of 8.6. UPDRS-ADL speech
scores ranged between 0 and 2 out of 4, with an average of 1.1. These scores indicate that most
participants with PD were mildly impaired. Participants with PD were scheduled to be tested
when their medication provided them with the best effect. Typically, this was one to two hours
into their medication cycle except for one participant, who only took medication once a day. All
participants with PD were able to drive to the experiment site, were ambulatory, and were able to
sustain the two-hour long experiment.

Table 3-1 Description of participants with PD

<table>
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<th>Code</th>
<th>Sex</th>
<th>Age (yr; mn)</th>
<th>Disease Duration</th>
<th>H &amp; Y Stage (Best/Worst)</th>
<th>UPDRS-ADL Score</th>
<th>MoCA© Score</th>
<th>Speech Intelligibility</th>
<th>Medication*</th>
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<td>66 1</td>
<td>1/1</td>
<td>4/1</td>
<td>30</td>
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<tr>
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<tr>
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<tr>
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<tr>
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<td>6/1</td>
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* Medication: A: Amantadine; C/L: Carbidopa/Levodopa; Ra: Rasagiline; Ro: Ropinirole; S: Selegiline.
Participants with PD were recruited through the University Retiree Volunteer Center (URVC) of the University of Minnesota, various PD support groups in the area, and the Struthers Parkinson’s Center in Golden Valley, Minnesota. Participants in the HC group were recruited through the URVC, family and friends within the PD support groups, University of Minnesota community, and ResearchMatch.com. All participants were native speakers of North American English.

3.2 Screening

Participant eligibility was performed in two steps. First, prior to scheduling an experimental session, potential participants were phone interviewed and were asked to provide their age, gender, native language, history of neurological disease and history of speech, language, and hearing disorders (See Appendix I for the Screening Form). Those who met criteria were scheduled and further screened for cognition and hearing on the day of experiment.

For cognition, participants were tested using the Montreal Cognitive Assessment (MoCA©). Permission to use MoCA© was obtained through email communication. The reason for cognitive screening was that many persons with PD are known to suffer mild cognitive impairment. This could have potentially affected their performance on the sensory tasks. MoCA© was chosen because it was shown to be sensitive to mild cognitive impairments in persons with PD, it is rapid and easy to administer, and it assesses a broad range of cognitive domains (Chou et al., 2010). In order to participate, a person needed to score at least 26 out of the 30 possible points. This cut-off score is known to exclude persons with any, including mild-cognitive impairment. Scores for both groups ranged between 27 and 30, and the mean score for both groups was 28.6. An unpaired t-test found no group difference for the cognitive scores. See Table 3-1 for MoCA scores for the PD group.
Hearing screening was performed using the MLP ToolBox for MATLAB (Grassi & Soranzo, 2009). There were two purposes for the hearing test. The first purpose was to determine if the participant’s hearing was at an acceptable minimal level for their age. A person needed to pass 40 dB HL at three frequencies (1, 4, and 8 kHz) in order to participate. Second, for those whose hearing thresholds fell within the aforementioned range, the thresholds were used to set the presentation level for the auditory discrimination task (to be described later). Persons who failed the cognitive or hearing screening were dismissed from the study. Three unpaired t-tests revealed no group difference for the hearing levels at any of the frequencies tested.

### 3.3 Experimental Tasks

There were three experimental tasks. This section describes each task in terms of stimuli, procedure, and relevant analyses and measurements.

#### 3.3.1 Speech Production Task

**Stimuli.** Two types of stimuli were used: eight words embedded in a carrier phrase and a short specially designed reading passage. The eight words began with either /s/ or /ʃ/ followed by one of the four vowels /ɛ/, /i/, /ɑ/, and /u/; they were said, seed, sod, sue, shed, she’d, shod, shooed. Participants read these words aloud, embedded within the carrier phrase “Say ___ again.” For the passage, participants read aloud The John Passage (Tjaden & Wilding, 2004; See Appendix II), which was designed to contain multiple occurrences of words that begin with /s/ or /ʃ/.

Both stimuli types were included for several purposes. First, both types are speech styles between the most natural (spontaneous) and the most controlled (reading words). The words-in-sentence material had balanced phonetic context by including both back and front, and high and low vowels in the English vowel space. The passage was included to compare results with
Tjaden and Wilding’s (2004), and to provide a means to describe intelligibility of the participants’ speech, to be described further on.

**Procedure.** Participants sat in front of a 24-inch computer monitor with a distance from the eyes of approximately 25 inches. Speech stimuli were presented via this monitor. The passage was presented in 22-point, and words in the carrier sentence in 30-point font. Participants were instructed to read aloud the stimuli in what they considered their comfortable, conversational rate, pitch and loudness level. The experimenter controlled the presentation of stimuli through a laptop connected to the presentation monitor. Participants wore a head-mounted microphone (Senheiser MZA 900 P-4), with a constant distance of 2 inches away from the lips. Audio recording was made using Sound Devices USBPre 1.5™ (Sound Devices, LLC) interfaced with PC computers at the sampling rate of 44.1 kHz at 16 bits per sample.

Each participant first read aloud the passage once. Following this they read aloud the words in the carrier sentence. The eight words in the carrier sentence formed one block, and the block was repeated 7 times. For each block, the words were randomized in order. Participants were offered a break after reading the passage and after each block.

**Acoustic Analysis and Measures.** Contrasts between /s/ and /ʃ/ were measured by the first moment difference (M1D). This measure has been used to describe spectral differences between these two sounds in previous studies of parkinsonian dysarthria (Kim et al., 2011; McRae et al., 2002; Tjaden & Wilding, 2004). Reduced M1D has been associated with impaired intelligibility in parkinsonian dysarthria (Kim et al., 2011).

Both types of stimuli (sentences and passages) were analyzed acoustically. Acoustic measurements were done using Praat (Boersma & Weenink, 2015). To obtain the dependent variable M1D, four steps were performed. First, for each recorded target word in the carrier sentence and in the passage, /s/ and /ʃ/ were marked in a textgrid. A boundary marker was put at
the zero crossing closest to the beginning of the turbulence noise (shown as boundary 1 in Figure 3-1). Another boundary marker was put at the zero crossing closest to the onset of the following vowel (boundary 2 in Figure 3-1). Next, a Praat script was run to extract M1 values for each sibilant from a 40-ms interval at the center between the two boundaries surrounding the sibilant. Third, the average M1 value of the /s/ tokens and that of the /ʃ/ tokens were calculated for each participant. For the fourth and final step, each participant’s M1D was calculated by subtracting average M1 of /ʃ/ from average M1 of /s/.

Figure 3-1 An example of boundary markers in the textgrids.

**Speech Intelligibility.** Four sentences (bold typeface in Appendix II) in the middle of the passage (Tjaden & Wilding, 2004) were excerpted from the audio recordings for each participant. Intensity of all excerpts was scaled to 70 dB (average RMS) using Praat, to minimize the effect of loudness on intelligibility (Tjaden & Wilding, 2004), so that the focus of intelligibility rating was more on articulatory impairment.
Eight judges assigned numbers to rate the intelligibility of the speech samples, using the free-modulus direction magnitude estimation. The judges ranged in age from 21 to 67 years old, all were native speakers of North-American English, and reported no history of any speech, language, hearing, or neurologic disorder. All were recruited from the University of Minnesota campus and gave informed consent.

The judges were instructed to rate how easy (i.e., how intelligible) they could understand the speech samples, by assigning higher numbers to those that were easier to understand and lower numbers to those that were more difficult to understand. The task instructions (see Appendix III) were adapted from Engen (1971). The judges were instructed to assign any number to the first speech sample presented to them. For successive samples, they were instructed to assign numbers proportional to the previous one they had just heard. For example, if they thought the sample was twice as easy to understand than the previous one, they should assign a number that was two times the rating they had given to the preceding sample.

The listening task was done in a quiet laboratory room, either for one judge or in a group of two judges. During the task, they listened to the speech samples through a pair of loud speakers approximately 5 feet from their ears, and wrote down their ratings in a table. Volume of the speech samples was set to approximately 68 dB SPL, measured from a judge’s chair. Each judge rated 40 speech samples: 20 speakers x 2 repetitions required by free-modulus direct magnitude estimation. There was a 4 second silent gap between each sample. Five sets of the same 40 samples were made using a different random order for each set. The listening task took approximately 20 minutes to complete. Intrajudge and interjudge reliability were determined by computing correlation coefficients from the ratings.

1 Twelve judges were recruited. Ratings of four judges were discarded for the following reasons. One judge was discarded because her ratings were negatively correlated with all other judges. A second judge was deleted because of poor intra-rater reliability, yielding non-significant correlation between his two repeated ratings. The remaining two were deleted because of low agreement with other judges, with p-values for correlation analyses larger than 0.05.
Ratings from the ten judges were converted into the same scale using the following procedure (Engen, 1971):

1. For every judge, each of the 40 ratings was converted to its logarithm (base 10).
2. A mean was calculated for the two repeated samples in each set, yielding 20 ratings per judge.
3. An individual grand mean of each judge’s 20 average ratings determined in Step 2 was then calculated, resulting in one value for each judge.
4. A group grand mean of the 7 individual judges obtained in Step 3 was calculated.
5. The group grand mean (step 4) was subtracted from each individual’s grand mean (Step 3).
6. The value found in Step 5 was added to the individual 20 ratings obtained for each judge in Step 2.
7. Finally, a mean score was calculated for each speaker from the values calculated in step 6.

3.3.2 Auditory Task

Stimuli. Stimuli for this task were created using Praat (Boersma & Weenink, 2015) by modifying the spectral features of a complex aperiodic sound (white noise) to create 25 stimulus tokens. These tokens varied along an acoustic continuum for the speech sounds of /s/ and /ʃ/. White noise with the bandwidth of 11 kHz (from 0 to 11 kHz) was shaped so that each stimulus token had three spectral peaks varying by their central frequencies, bandwidths, and amplitudes (Winn, Rhone, Chatterjee, & Idsardi, 2013). Token 1, representing /ʃ/, was located at one end of the continuum and Token 25, for /s/, at the other.
Creation of the stimuli for this study was adapted from Winn and colleagues’ (2013) who studied categorization of /s/ and /ʃ/ in cochlea implant users. Further consideration was given into creating finer step sizes than Winn et al.’s (2013). In what follows is a description of this process.

In creation of their stimuli, Winn and colleagues first extracted spectral parameters from natural productions of /s/ and /ʃ/ by native speakers of North-American English. Next, they created nine stimulus items along this /s/-/ʃ/ continuum. The distance of spectral peak frequencies between each adjacent item were calculated on a log scale; as a result, the spectral peaks of adjacent items differed from 200 to 500 Hz.

Because the purpose of this study was to examine participants’ discrimination threshold and not categorization of /s/ and /ʃ/, smaller steps were needed for a more precise estimation. This need was based on the findings of Perkell et al. (2004). Perkell and colleagues examined neurologically healthy participants’ ability in discriminating synthesized sibilants. They created seven items along a /s/-/ʃ/ spectral continuum differing in M1 values. They presented these items in triads to their participants. The first two items in a triad differed by one, two or three steps, and the third item was the same as either the first or the second stimulus item. Participants indicated whether the third was the same as the first or the second stimulus item. Perkell and colleagues did not report the exact size of their steps, but based on the reported values from the two sibilants from their production task, it is likely that their steps were around 160 to 200 Hz.

Their results showed a floor effect for the 1-step comparison and a ceiling effect for the 3-step

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2 Perkell et al. (2004) examined the relationship between participants’ production of /s/ and /ʃ/ and auditory acuity. For their auditory task, they created their seven stimuli by adopting the spectral means of /s/ and /ʃ/ from natural productions, and linearly interpolating six steps into the /s/-/ʃ/ continuum. They did not report the spectral means for the stimuli or their steps. For their production task, they reported the average spectral means for /s/ and /ʃ/ were 5927 and 4962 Hz for women, respectively, and 5776 and 4575 Hz for men. Thus the six steps would be 160-200 Hz for women and men, respectively.
comparison for most participants. Even for their 2-step comparisons, half of the participants reached 100% correct response rate. Thus, a one-step distance was too narrow, and a two-step distance was too wide. Therefore, it was inferred that, for their participants, the discrimination threshold was most likely somewhere between 200 to 400 Hz.

Based on Perkell et al.’s (2004) results, it was determined that the steps by Winn et al. (2013) were too large for the purpose of the present study, and smaller steps were needed. Thus, midway between adjacent tokens of Winn et al.’s (2013) nine tokens, an extra token was created, resulting in 17 tokens. As a result, the spectral peaks of adjacent tokens differed for about 200 Hz. The brown dashed lines in Figure 3-2 demonstrate where these tokens were inserted.

Yet, after running a few pilot participants it was found that the 200-Hz difference was still too large to determine a threshold for some participants. They were able to discriminate the one-step comparisons better than chance. Therefore, a second interpolation procedure was performed within the center tokens in order to add finer comparisons. Rather than adding additional items between the 17 tokens and nearly doubling the number of stimuli, more were created and added in the region of the center token. Because the center stimulus item was the standard for comparison, it was reasoned that smaller steps in this region would yield a wider range of responses. Eight additional items were created by first generating four tokens half way between each of the five center stimuli (shown as blue dotted lines in Figure 3-2). Second, two tokens were generated half way between the center and its two adjacent stimuli on either side (shown in red dotted lines in Figure 3-2). Third, an additional two tokens were created by placing them between the center token and the two new stimuli just created (shown in orange dotted lines in Figure 3-2). As a result, spectral peak frequencies around the center few tokens differed as small as 12 Hz (See
Winn and colleagues (2013) did their interpolation on a log scale, but reported their spectral peak frequencies in Hz. In order to replicate their methods, I used log_{10} of the reported Hz values when creating these stimulus items. In Table 3-2, showing the frequency, bandwidth, and relative amplitude for each peak of the stimulus tokens, the frequency values were converted back to Hz for easy reading. Bandwidth and relative amplitude were both computed on a linear scale (Winn et al., 2013). Figure 3-3 shows the spectra of tokens 1 (representing /ʃ/), 13 (standard), and 25 (representing /s/).
Table 3-2 Parameters for the auditory stimuli.

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* Freq: Frequency. BW: Bandwidth. Rel Amp: Relative Amplitude to the second peak.
Procedure. Participants listened to a sequence of three sounds of 240 ms duration, with 500-ms inter-stimulus gaps. For each trial, two of the sounds presented were the standard, and the other was a comparison. The standard was always the token at the center point along the continuum, Token 13. The comparison was one of the other tokens (Token 1-12 or 14-25), presented randomly within the three-sound sequence (first, second, or third). For each trial, the participants’ task was to identify which of the three sounds was different from the other two. Twenty-four

Figure 3-3 Spectra of Token 1 (top), Token 13 (middle), and Token 25 (bottom).
trials, with each comparison presented once, made a block. Each participant performed six blocks for a total of 144 trials. Within each block, the comparisons were presented randomly.

A computer controlled the experiment using a custom-written MATLAB program that presented the trials and recorded the responses. Participants wore headphones (AKG K240) and sat in front of a computer monitor interfaced with the computer. The output level was adjusted to approximately 50 dB SPL above each participant’s mean absolute hearing thresholds obtained from the 4 and 8 kHz hearing screenings. This was to account for their hearing at relatively high frequencies where the spectral energy of /s/ and /ʃ/ is located. For each trial, participants heard the three-sound sequence while looking at the computer monitor showing three virtual response buttons (Figure 3-4A). When each sound in the 3-sound sequence played, the corresponding button on the screen flashed. This was done to better help a participant affiliate a sound to a number within a sequence. Participants verbally reported which sound they heard was different from the other two. The experimenter then selected the button for a participant; the experimenter did this in order to avoid motor difficulties such as motor perseverance affecting the performance of the participants with PD.
Figure 3-4 Presentation screens for auditory task. A: The interface for participants’ response. B: A corresponding button flashes when a stimulus sound was playing.

Measures. In order to measure how acute a participant was in discriminating the auditory stimuli, a just-noticeable-difference threshold ($\text{JND}_{\text{AUD}}$) and an area of uncertainty ($\text{AOU}_{\text{AUD}}$) were calculated (shown in Figure 3-5). This was done in three steps:

1. For each participant, the proportion of correct responses (PCR) was calculated (shown as unfilled circles in Figure 3-5) for each step. Each PCR was calculated from trials with
comparisons that were equal steps on either side of the standard (Token 13). For example, the 
PCR of 12-step difference was calculated by dividing the sum of the number of correct responses 
of Token 1 and that of Token 25. Likewise, 11-step PCR was calculated from responses to 
Token-2 and Token-24 trials, and so on.

2. A sigmoid curve was fitted to the 12 PCRs, generating a psychoacoustic function for 
each participant. The fitting of the function curves was done by the \texttt{glm()} function of the 
statistical software R. An example of the fitted function curve is shown in black in the figure.

3. JND\textsubscript{AUD} and AOU\textsubscript{AUD} were identified along this function curve (See Figure 3-5 as an 
example). JND\textsubscript{AUD} is defined as the difference in steps corresponding to 0.67 PCR, which is half 
way between chance level (0.33) and perfect performance (1.00). AOU\textsubscript{AUD}, defined as the 
interval between differences corresponding to 0.52 and 0.82 CRR (0.3 around JND\textsubscript{AUD}), was also 
calculated, to show how certain a participant’s responses were around the threshold.
Figure 3-5 Example for identifying measures of auditory acuity. The black dots mark the correct response rates for the differences. The solid black curve is the psychoacoustic function. The red lines show how the JND threshold was identified. The blue lines mark the upper and lower boundaries of the area of uncertainty.

3.3.3 Tactile Task

Equipment. Tactile acuity of the tongue tip mucosa was tested using JVP Domes (Stoelting Co.). The JVP Domes are probes used to test cutaneous spatial resolution. Each probe has a dome-
shaped head with a columnar handle. On the head are equidistant grooves and ridges aligned parallel to each other (See Figure 3-6). There are eight probes, differing in the width of ridges and grooves (0.35, 0.5, 0.75, 1.0, 1.25, 1.5, 2.0 and 3.0mm).

![Figure 3-6 An illustration of the JVP Domes.](image)

**Procedure.** Participants were seated and blindfolded to prevent them from seeing the stimuli. For each trial, the participant protruded the tongue tip and the experimenter pressed the head of a probe against the participant’s tongue tip, with the gratings aligned to one of two possible orientations: vertical and horizontal. Care was taken to apply the same amount of pressure for each token.

Before data collection, the experimenter instructed the participants for the procedure in three steps. First, in order to prevent the jaw and tongue muscles from becoming fatigue within only a few trials, the participants were guided to slightly protrude the tongue, just enough to show the tongue blade. This way a minimal portion of the tongue was protruded but when the dome was gently pressed to the tongue tip, the lips were not touched. Participants were also instructed to minimize the jaw opening to reduce muscle efforts. Occasionally a mirror was used to help guide participants for tongue protrusion. Next, participants were instructed to indicate which
orientation the gratings were at by hand gestures using their dominant hand. They were instructed to point the index finger upward to indicate a vertical orientation, and hold the four fingers down to indicate horizontal orientation. Responses were made on a two-interval-forced-choice paradigm. Third, once the participant had learned the tongue-protruding and response methods, at least five practice trials were administered using the three larger-resolution domes (3.0, 2.0 and 1.5 mm) presented in both orientations.

The data collection consisted of five blocks. In each block, the eight grating resolutions were presented for both orientations twice, and in random order, yielding 32 trials. Random order of the presentation within a block was determined prior to testing a participant. A participant performed 160 trials in total (5 blocks x 32 tokens). The probes were soaked in an antibacterial solution for at least 20 minutes before testing a new participant.

Measures. Similar to the auditory task, a tactile JND threshold (JND<sub>TAC</sub>) and a tactile area of uncertainty (AOU<sub>TAC</sub>) were determined. This was done in three steps:

1. For each participant, a PCR was calculated for each dome resolution, by dividing the number of correct responses by the number of trials for that resolution. This yielded eight tactile PCRs shown in Figure 3-7 as unfilled circles;

2. A sinusoidal curve was fitted to the eight PCRs, generating a psychophysical function for each participant. The fitting of the function curves was done by the \texttt{glm()} function of the statistical software R. The figure shows an example curve in black. Dome resolution was plotted on the abscissa, and PCR was plotted on the ordinate; and

3. JND<sub>TAC</sub> and AOU<sub>TAC</sub> were identified along this function curve (as shown in the figure). The JND<sub>TAC</sub> is defined as the dome resolution corresponding to 0.75 PCR, which is half way between chance level (0.50) and perfect performance (1.00). The AOU<sub>TAC</sub>, defined as the interval
between differences corresponding to 0.6 and 0.9 CRR (0.3 on either side of $JND_{TAC}$), was also calculated, to show how certain a participant’s responses were around $JND_{TAC}$.

Figure 3-7 Example for identifying measures of tactile acuity. The black dots mark the correct response rates for the dome resolutions. The black curve is the fitted psychophysical function. The red lines show how the JND threshold was identified. The blue lines mark the upper and lower boundaries of the area of uncertainty.
3.4 Experiment-wise data analysis

Data analyses used two methodologies: testing of group difference between the HC and PD groups and correlational analysis. To test for group differences, each measure was submitted individually to statistical tests. M1D values from the sentences and the passages were submitted to a mixed effect ANOVA, with Group (PD vs. HC) as between-subject effect and Task (sentence vs. passage) as within-subject effect.

Group difference in measures of tactile acuity ($JND_{TAC}$ and $AOU_{TAC}$) was tested in two one-tailed unpaired t-tests. Because the auditory acuity data for $JND_{AUD}$ and $AOU_{AUD}$ were on ordinal scale, they were submitted to two one-tailed Mann-Whitney tests.

Correlation analyses were done separately for each group, and they were of two types. First, relationships among the dependent variables were examined. M1D and auditory acuity measures were submitted to eight (M1D from two materials x two auditory measures x two groups) Spearman’s rank correlation tests, and relationship between M1D and tactile acuity measures were tested in eight Pearson’s correlation tests. In addition, in order to know whether measures from the two sensory domains are correlated, the sensory-acuity measures were submitted to eight (two auditory measures x 2 tactile measures x 2 groups) Spearman’s tests.

Second, relationships between the dependent variables from the three tasks were submitted to correlation tests to examine whether there were additional factors. For both groups, these variables were tested for correlations with age, average absolute hearing threshold of 4 and 8 kHz, MoCA scores, and speech intelligibility scores. For the PD group, variables were tested for correlations with years post-diagnosis, UPDRS-ADL scores, and UPDRS-ADL speech scores. These correlation analyses were done using Spearman’s tests whenever the test involved the auditory acuity measures, and all others were done using Pearson’s tests.
Chapter 4 Results

4.1 Speech production

4.1.1 Spectral contrast between /s/ and /ʃ/

Means and standard deviations of M1D are shown in Table 4-1. Box-and-whisker plots of M1D values for the two groups are shown in Figure 4-1. The left panel shows M1D from the words in sentences, and the right panel shows M1D from the passage. The data show that there was no statistically significant group difference for M1D for both speaking tasks. A mixed-effects ANOVA showed significant within-subject effect of speech material, \( F(1, 18) = 11.23, p = 0.004 \); but the between-subject effect of group was not significant, \( F(1, 18) = 1.15, p = 0.29 \).

<table>
<thead>
<tr>
<th>Group</th>
<th>Sentences</th>
<th>Passages</th>
</tr>
</thead>
<tbody>
<tr>
<td>HC</td>
<td>3780 (794)</td>
<td>3082 (1147)</td>
</tr>
<tr>
<td>PD</td>
<td>3163 (878)</td>
<td>2886 (774)</td>
</tr>
</tbody>
</table>
4.1.2 Speech intelligibility

Inter-rater reliability analyses yielded significant correlations among judges' ratings, correlation coefficients ranged between 0.55 and 0.92, $p < 0.01$. Intra-rater reliability analyses showed significant correlations for every judge’s two repeated ratings; correlation coefficients ranged from 0.6 to 0.98, $p < 0.001$.

Box-and-whisker plots of intelligibility ratings are shown in Figure 4-2. Ratings for the PD group ranged from 1.01 to 1.61, and those for the HC group ranged from 1.45 to 1.60. Medians and inter-quartile ranges are 1.57 and 0.08 for PD and 1.58 and 0.05 for HC. A one-tailed Mann-Whitney U test showed no group difference, $U = 58.5, p = 0.27$. See Table 3-1 for intelligibility ratings for participants with PD.
Figure 4-2 Box-and-whisker plots for intelligibility scores for the two groups. The open circles show outliers.

4.2 Sensory acuity

4.2.1 Auditory acuity

Medians and inter-quartile ranges of JND_{AUD} and AOU_{AUD} for the two groups are shown in Table 4-2. Figure 4-3 shows box-and-whisker plots of the acuity values by participant group. As
seen in Figure 4-3, the PD group showed elevated JND\textsubscript{AUD} and larger AOU\textsubscript{AUD}. But, one-tailed Mann-Whitney U tests only yielded significant group difference for AOU\textsubscript{AUD} (U = 13, \( p = 0.002 \)), and not JND\textsubscript{AUD} (U = 31, \( p = 0.08 \)).

<table>
<thead>
<tr>
<th>Group</th>
<th>JND\textsubscript{AUD} (Steps)</th>
<th>AOU\textsubscript{AUD} (Steps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PD</td>
<td>4.52 (1.06)</td>
<td>3.66 (1.23)</td>
</tr>
<tr>
<td>HC</td>
<td>3.92 (0.48)</td>
<td>1.85 (1.10)</td>
</tr>
</tbody>
</table>
Figure 4-3 Box-and-whisker plots for auditory acuity measures. The left panel shows box plots for JND_{AUD}, and the right panel shows box plots for AOU_{AUD}. The open circle shows an outlier.

A scatter plot of auditory acuity measures for individual participants is shown in Figure 4-4. As can be seen in the plot, most of the participants with PD had greater values for at least one of the two measures compared to the healthy participants, one participant with PD performed similar
to healthy participants, and one healthy participant had $\text{JND}_{\text{AUD}}$ that fell outside of the range of other healthy participants.

Figure 4-4 Measures of auditory acuity for PD (filled circles) and HC (unfilled triangles). The ordinate shows $\text{JND}_{\text{AUD}}$ and the abscissa shows $\text{AOU}_{\text{AUD}}$. The horizontal and vertical dashed lines mark the median $\text{JND}_{\text{AUD}}$ and $\text{AOU}_{\text{AUD}}$ of the HC participants, respectively.
4.2.2 Tactile acuity of the tongue tip

Means and standard deviations of JND_{TAC} and AOU_{TAC} are shown in Table 4-3. Box-and-whisker plots are shown in Figure 4-5. As seen in Figure 4-5 and confirmed by one-tailed t-tests, persons with PD showed significantly elevated JND_{TAC} (t = -2.23, p = 0.02) and larger AOU_{TAC} (t = -3.55, p = 0.002) compared to the healthy participants.

Table 4-3 Means (standard deviations) for tactile acuity measures by group.

<table>
<thead>
<tr>
<th>Group</th>
<th>JND_{TAC} (mm)</th>
<th>AOU_{TAC} (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PD</td>
<td>0.71 (0.20)</td>
<td>0.44 (0.23)</td>
</tr>
<tr>
<td>HC</td>
<td>0.56 (0.06)</td>
<td>0.15 (0.12)</td>
</tr>
</tbody>
</table>
Figure 4-5 Box-and-whisker plots for tactile acuity measures. The left panel shows JND\textsubscript{TAC} and the right panel shows AOU\textsubscript{TAC}. The open circles show outliers.

A scatter plot of the tactile acuity measures for individual participants is shown in Figure 4-6. As seen in the plot, most of the participants with PD had greater values for at least one of the two measures compared to the healthy participants. Of the ten PD participants, six showed greater values in both JND\textsubscript{TAC} and AOU\textsubscript{TAC}, two had greater AOU\textsubscript{TAC}, one had elevated JND\textsubscript{TAC},
and one performed within the range of the healthy participants for both measures. Two healthy participants' $\text{JND}_{\text{TAC}}$ were outside of the range of other healthy participants, and one of them also showed larger $\text{AOU}_{\text{TAC}}$.

Figure 4-6 Measures of tactile acuity for individual participants. Filled circles show measures of participants with PD, and unfilled triangles show those of healthy controls. The ordinate shows $\text{JND}_{\text{TAC}}$ and the abscissa shows $\text{AOU}_{\text{TAC}}$. The horizontal and vertical dashed lines mark the mean $\text{JND}_{\text{TAC}}$ and $\text{AOU}_{\text{TAC}}$ of the HC participants, respectively.
4.3 Correlation analyses

4.3.1 Relationship between M1D and auditory acuity

For each group, four Spearman’s correlation tests were run on $\text{JND}_{\text{AUD}}$ and $\text{AOU}_{\text{AUD}}$ by M1D from sentences and passages. Resulting $p$-values and correlation coefficient $\rho$- (rho) values are shown in Table 4-4. For the PD group, although the correlation coefficients were all negative, none of the tests yielded significant $p$-values. For healthy participants, no correlation was found between their auditory acuity measures and M1D values from either sentences or passages. Scatter plots of the relationships are shown in Figure 4-7.

| Table 4-4 Statistics from correlation tests for auditory measures and M1D values. |
|-----------------|---------|---------|---------|
|                  | PD      |         | HC      |
|                  | $\rho$ (rho) | $p$   | $\rho$ (rho) | $p$ |
| M1D from sentences | $\text{JND}_{\text{AUD}}$ | $-0.01$ | $0.50$ | $0.22$ | $0.73$ |
|                  | $\text{AOU}_{\text{AUD}}$ | $-0.41$ | $0.12$ | $-0.26$ | $0.23$ |
| M1D from passage | $\text{JND}_{\text{AUD}}$ | $-0.38$ | $0.13$ | $0.28$ | $0.78$ |
|                  | $\text{AOU}_{\text{AUD}}$ | $-0.30$ | $0.20$ | $-0.27$ | $0.22$ |

The $p$-values are based on one-tailed correlation tests, assuming negative correlations following Ghosh et al. (2010).
Figure 4-7 Scatter plots for auditory measures and M1D values. Top-left: Sentence M1D and JND\textsubscript{AUD}. Top-right: Sentence M1D and AOU\textsubscript{AUD}. Bottom-left: Passage M1D and JND\textsubscript{AUD}. Bottom-right: Passage M1D and AOU\textsubscript{AUD}. In each graph, filled circles show values from PD, and unfilled triangles show values from HC. The solid and dashed lines show linear regression lines for PD and HC, respectively.
4.3.2 Relationship between M1D and tactile acuity measures

To test for relationships between M1D and tactile acuity measures, four Pearson’s correlation tests were run for each group. Resulting r- and p-values are shown in Table 4-5. For the PD group, negative correlation was found between sentence M1D and $JND_{TAC}$, indicating that those who demonstrated reduced tactile acuity of the tongue tip produced smaller contrasts between /s/ and /ʃ/ for their sentences. For healthy participants, no significant correlation was found between their tactile acuity measures and M1D values from either sentences or passages. Scatter plots of the relationships are shown in Figure 4-8.

<table>
<thead>
<tr>
<th></th>
<th>PD</th>
<th></th>
<th></th>
<th>HC</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$JND_{TAC}$</td>
<td>$r$</td>
<td>$p$</td>
<td>$r$</td>
<td>$p$</td>
</tr>
<tr>
<td>M1D from sentences</td>
<td></td>
<td>$-0.72$</td>
<td>$0.009^{**}$</td>
<td>$0.04$</td>
<td>$0.55$</td>
</tr>
<tr>
<td></td>
<td>$AOU_{TAC}$</td>
<td>$-0.36$</td>
<td>$0.16$</td>
<td>$0.41$</td>
<td>$0.88$</td>
</tr>
<tr>
<td>M1D from passage</td>
<td>$JND_{TAC}$</td>
<td>$-0.31$</td>
<td>$0.19$</td>
<td>$-0.03$</td>
<td>$0.47$</td>
</tr>
<tr>
<td></td>
<td>$AOU_{TAC}$</td>
<td>$-0.22$</td>
<td>$0.27$</td>
<td>$0.23$</td>
<td>$0.74$</td>
</tr>
</tbody>
</table>

** $p < 0.01$

† The $p$-values are based on one-tailed correlation tests, assuming negative correlations following Ghosh et al. (2010).
Figure 4-8 Scatter plots for tactile acuity measures and M1D values. Top-left: Sentence M1D and JNĐ_{TAC}. Top-right: Sentence M1D and AOÛ_{TAC}. Bottom-left: Passage M1D and JNĐ_{TAC}. Bottom-right: Passage M1D and AOÛ_{TAC}. In each graph, filled circles show values from PD, and unfilled triangles show values from HC. The solid and dashed lines show linear regression lines for PD and HC, respectively.
4.3.3 Relationship between auditory and tactile acuity

Correlations between the auditory and tactile measures for individual participants were tested using four Spearman’s correlation tests for each group. None of the tests between the two sensory domains turned out significant (p-values ranged from 0.06 to 0.55, See Appendix IV and V for correlation matrices).

4.4 Dependent variables and other possible factors

For correlation coefficients and p-values for every individual test, see appendices IV and V.

4.4.1 Relationship between M1D and other factors

For participants with PD, no significant correlations were found between sentence M1D or passage M1D and age, absolute hearing threshold, MoCA scores, UPDRS-ADL scores, or Hoehn and Yahr stages. A positive correlation was found between passage M1D and UPDRS-ADL Speech scores (ρ = 0.83, p < 0.01), indicating participants who rated their own speech as more affected also read the passage with larger M1D. No correlation was found between M1D and intelligibility scores.

For the HC participants, neither sentence M1D nor passage M1D was correlated with age, absolute hearing threshold, or MoCA scores. Positive correlations were found between sentence M1D and intelligibility scores (ρ = 0.68, p = 0.03) and between passage M1D and intelligibility scores (ρ = 0.74, p = 0.01), indicating HC participants who produced larger M1D were rated as more intelligible.
4.4.2 Relationship between auditory acuity measures and other factors

For both groups, neither JND\textsubscript{AUD} nor AOU\textsubscript{AUD} were associated with age (p > 0.20) or absolute hearing threshold (p > 0.13). For healthy participants, MoCA scores were significantly correlated with JND\textsubscript{AUD} (ρ = -0.66, p = 0.04), but not AOU\textsubscript{AUD}. For PD, there were no significant correlations between auditory acuity measures and MoCA scores, years-post diagnosis, UPDRS-ADL, UPDRS-ADL speech scores, or Hoehn and Yahr stages.

4.4.3 Relationship between tactile acuity measures and other factors

For both groups, tactile acuity measures were not correlated with either age or MoCA scores. For participants with PD, tactile acuity measures were not correlated with years post-diagnosis, UPDRS-ADL scores, UPDRS-ADL speech scores, or Hoehn and Yahr stages.
Chapter 5 Discussion

This dissertation investigated whether two speech-related senses used in maintaining intelligible speech, audition and somatosensation, are impaired in PD. And, if impairment was found in these two senses were they correlated to atypical speech found in PD. Spectral contrast of the sibilants /s/ and /ʃ/ is often reduced in the speech of persons with PD and was found correlated to their decreased speech intelligibility (Kim et al., 2011; McRae et al., 2002; Tjaden & Wilding, 2004). In healthy speakers, the degree of spectral contrast between /s/ and /ʃ/ is known to be correlated to their auditory acuity in discriminating spectral shapes and tactile acuity on the tongue tip (Ghosh et al., 2010; Perkell et al., 2004). Participants with PD were compared to age and gender matched healthy adults for (a) the spectral contrast, M1D, of /s/ and /ʃ/ extracted from their speech; (b) the degree of auditory acuity in discriminating between sounds of different spectral shapes; and (c) the degree of tactile acuity to stimuli placed on the tongue tip; and (d) correlations were examined for M1D to auditory acuity and M1D to tactile acuity for both groups. Overall, my results in relation to the stated hypotheses found that participants with PD had reduced auditory and tactile acuity when compared to the HC group. And, a relationship was found in the spectral contrast for the production of the two sibilants with their tactile acuity, but only in the PD group. Although a sensory-speech correlation was found, no statistically significant group differences were found for spectral contrast of the two sibilants during speech production.
5.1 **Hypothesis 1: Participants with PD will show smaller /s/-/ʃ/ M1D**

Previous studies have identified several acoustic anomalies in speech of persons with PD, including reduced contrast between /s/ and /ʃ/, measured by M1D (McRae et al., 2002; Tjaden & Wilding, 2004). Given these findings, it was predicted that participants with PD would produce smaller /s/-/ʃ/ M1D. Results showed no statistically significant difference in M1D between the two groups for both reading tasks.

Although no descriptive statistics were provided in the two aforementioned studies (McRae et al., 2002; Tjaden & Wilding, 2004), M1D values derived from Figure 5 in Tjaden and Wilding ranged from 500-2800 Hz. The M1D values for this study were larger, showing greater acoustic separation, and ranged from 1709-4469 Hz. The smaller M1D values found in the earlier studies could be attributed to greater severity of judged speech impairment in their participants with PD. Most of the participants with PD in McRae et al. (2002) and Tjaden and Wilding (2004) were rated to have moderate to severe dysarthria. Further, their PD participants were rated to have significantly lower intelligibility scores than their healthy participants. No clinical ratings of severity were acquired for this study, but no significant difference between groups was found with regard to intelligibility ratings. Only three of the PD participants in this study were rated to have lower intelligibility scores than those in the HC group (below the first quartile of HC).

It is also possible that the use of M1D to capture the acoustic differences between the two sibilants /s/ and /ʃ/ may have limited the results. The selection of this measure was decided based on previous studies on speech in PD and those on sensory-speech associations for sibilants. To calculate M1D, the mean M1 of /ʃ/ was subtracted from the mean M1 of /ʃ/. However, using this measure only captures the central tendency of the participants’ sibilant production, and ignores intra-speaker variability. Could a more variable /s/ and /ʃ/ production and/or overlapping...
distributions of /s/ and /ʃ/ M1 values characterize the /s/-/ʃ/ production of participants with PD? To examine this possibility, probability density plots for individual participants’ M1’s from sentences (see Appendix VI) were plotted and inspected. It appears that four of the participants with PD showed overlapping distributions of /s/ and /ʃ/ M1’s, although two healthy participants also showed similar overlap. Given these observations, there most likely was no acoustic difference, observed with standard methods of measurement, between the two speaker groups. This corresponds to the ratings of their own speech as being mildly impaired and intelligibility ratings of independent listeners showing no difference between the two groups studied.

5.2 Hypothesis 2: Participants with PD will show reduced auditory acuity

The PD group showed impaired auditory acuity in discriminating sounds differing in spectral shapes in relation to /s/ and /ʃ/. The importance of audition to producing normal speech has been presented in Chapter 2. Specifically as it pertains to the maintenance of sibilant contrast, Lane and Webster (1991) showed that when speakers were deafened postlingually, /s/-/ʃ/ M1D reduced significantly. This study is the first to report in PD, to my knowledge, auditory impairment in perceiving spectral characteristics relevant to specific phonetic features. Previous work has reported auditory impairment in perceiving global loudness of reading materials (Clark et al., 2014; Ho et al., 2000) and detecting the difference of loudness and frequency of pure tones (Troche et al., 2012).

It should be noted that reduced auditory acuity found in this study is unlikely to be attributed to hearing sensitivity since there was no difference in the hearing thresholds of the two groups. Also, care was taken to set the intensity level of the auditory stimuli well above each participant’s threshold. In addition, there was no difference in the two groups’ MoCA scores that may have suggested a possible cognitive component with regard to their responses.
5.3 Hypothesis 3: Participants with PD will show reduced tactile acuity, demonstrated by elevated JND and enlarged AOU

Studies on kinesthesia of the trunk and limbs in persons with PD have found somatosensory deficits (e.g., see review in Konczak et al., 2009). Relatively less is known about speech-related somatosensation in PD. A small set of studies has shown defective somatosensation in relation to the speech effectors (Hammer & Barlow, 2010; Schneider et al., 1986). For this study, the hypothesis was confirmed that participants with PD would show decreased tactile acuity of the tongue tip.

It should be noted that there was no correlation between auditory acuity and tactile acuity in either group. This finding was in line with Perkell et al. (2004) and Ghosh et al. (2010), both reporting no correlation of variables between the auditory and somatosensory domains in their healthy young adult speakers. The authors did not discuss it, but the uniform finding of no-correlation in this study and theirs may have reflected variation among individual speakers. In this study, it could suggest that individual participants differed in how they use the two senses to guide their articulation, or that the disease disrupted the two sensory systems in different degrees and at different stages of the disease.

5.4 Hypothesis 4: There will be negative correlations between M1D and a) auditory and b) tactile acuity measures in both groups

This hypothesis was partially confirmed. Only tactile acuity was negatively correlated with the /s/-/ʃ/ M1D in the PD group but not for the HC group.

Hypothesis 4a) There will be a negative relationship between auditory acuity and M1D. No correlation was found for this sub-hypothesis. The association between auditory
acuity and /s/-/ʃ/ M1D has been documented in healthy young adult speakers (Ghosh et al., 2010; Perkell et al., 2004). For PD, impaired auditory perception was found for loudness (Clark et al., 2014; Ho et al., 2000) and pure tones (Troche et al., 2012), but only Ho et al. (2000) suggested an association between perception deficits to their participants’ impaired speech production. Ho and colleagues’ participants with PD read the stimuli passage quieter than healthy participants but estimated themselves as louder, demonstrating a mismatch between perception and production. Unlike Ho et al.’s (2000) findings on loudness, this study focused on a specific phonemic spectral characteristic and its correlation to the production of related speech sounds.

It was unexpected that no relationship between production and audition was found in this study, especially because the PD group showed reduced auditory acuity. But, the small number of participants may have contributed to the findings. If a larger group of participant was included, the relationships may have been statistically significant.

**Hypothesis 4b) There will be a negative relationship between tactile acuity and M1D.** This sub-hypothesis was confirmed by a significant negative correlation found for the tactile-acuity measure JND_{TAC} to sentence M1D for the PD group. This association was previously reported in healthy speakers (Ghosh et al., 2010), suggesting the importance of specific somatosensory discrimination to production of relevant speech sounds. The only previous report of a similar association in PD was by Hammer and Barlow (2010), showing that PD speakers’ decreased laryngeal tactile sensitivity was associated with shortened VOT of their voiceless stop consonant /p/.

The finding that /s/-/ʃ/ M1D was correlated with tactile acuity but not auditory acuity is interesting. Perkell (2012) has suggested that unlike most other English consonants, /s/ and /ʃ/ have prominent auditory as well as somatosensory cues, providing important sensory feedback
for both sibilants. Ghosh et al. (2010) supported this suggestion and reported similar strengths of correlation for the two senses ($r^2 = 0.17$ for auditory and 0.19 for tactile acuity) to /s/-/ʃ/ contrast in healthy young adults. But in this study, although both senses were impaired in PD, only tactile acuity appeared to account for the variation of M1D. As mentioned above, the non-correlation of auditory acuity to M1D could be due to the small sample size. But it could not be ruled out that participants with PD did not use the two sensory systems equally to guide their sibilant production. They could have weighted tactile feedback more than auditory feedback, but this requires further investigation.

5.5 General Discussion

5.5.1 Sensory-speech relationship in PD

With no significant observable difference in the production of the two sibilants, finding a significant correlation with auditory impairment was difficult. But, production of /s/ and /ʃ/ both require relatively precise tongue position, resulting in specific auditory and tactile feedback. But as mentioned, severity of PD in these participants was mild, as indicated by their ability to drive, ambulate, their self rating of the disease using the UPDRS-ADL, the self-rating of their speech, and the rating of intelligibility by a group of independent listeners. Perhaps sensory impairment related to speech manifests itself earlier than a motor-speech impairment. Konczak et al. (2009), reviewing proprioception of the trunk and limbs, suggested that somatosensory deficits might exist very early in the disease, before motor deficits of the trunk and limbs emerge.

5.5.2 Future studies

Previous studies have established that PD impairs somatosensation of the trunk and limbs. Several studies, including this one, found somatosensory deficits in speech organs such as the jaw
and the tongue. Thus, somatosensory deficits in PD are not only present in the trunk and limbs, but also in the speech organs. Further, both speech and trunk-and-limb studies on PD showed that the defective somatosensation was correlated to motor impairment. This may imply some similarity between speech and trunk-and-limb motor controls and so there is a need of studies across speech and non-speech motor control systems for PD.

Furthermore, other speech components should be studied to broaden our knowledge of the sensory-speech relationships in PD. As one example, acoustic studies have identified abnormal vowel production in PD, demonstrated by reduced vowel space and formant transitions. Is abnormal vowel production correlated to impaired auditory perception of vowel formants and/or somatosensation of the tongue? Another example regards monotonicity in PD. Acoustic studies have found speakers with PD showed decreased pitch variability in their speech. One study on auditory perception in PD found that persons with PD showed decreased auditory acuity in discriminating frequency of pure tones. Is abnormal pitch variability in their speech correlated to impaired auditory discrimination of frequency? Studying more speech components will deepen our understandings of sensory relationships to speech in PD.

5.6 Conclusions

This study is the first systematic investigation examining the association of sibilant production to related impairment of audition and somatosensation in PD. The findings suggest that sensory deficits may play some role in speech impairment in PD. The predicted auditory-speech correlation was not found and needs further investigation. The findings deepened our knowledge about speech in PD, and suggest further investigations into this sensory-speech relationship.
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science and practice of LSVT/LOUD: Neural plasticity-principled approach to treating


Appendices

Appendix I Phone Screening Form

Date _______________
Experimenter __________

Potential Participant ID ________ Potential Group (PD or HC) ________
Age ________ Gender ________
Handedness ________ Native language ________

Do you have any history of speech/language/hearing disorders or have you received any speech/language therapy? ______
   If yes, please list all:
   When were the therapy/therapies? ________
   What disorder(s) if you recall? ________
Are you wearing a hearing aid? ________
Have you ever been diagnosed with any neurological disease? ________
   If yes, please list all:
   When were you diagnosed? ________
   What disease(s), if you recall? ________
Have you ever had a stroke? ________
Have you ever had any head injury? ________
Have you ever been diagnosed with any cognitive disorder? ________
   If yes, please list all:
   When were you diagnosed? ________
   What cognitive symptom(s), if you recall? ________
Do you currently wear dentures? ________
Have you ever had any oral surgery? ________

Additional Questions for Persons with Parkinson’s Disease
Have you received any surgery as a treatment for Parkinson’s disease? ________
   If yes, is it deep brain stimulation? ________
Appendix II The John Passage (Tjaden & Wilding, 2004)

John planted a seed in his garden. He dug into the sod while humming a tune from the radio. The song was a tad off key, but John persisted because he was in a keyed up frame of mind from the long work week. As he worked, John's buddy Todd walked by. Todd was thought to be somewhat of a cad by most, but was known for his stories. He spun a tale about an eccentric woman who sat on her stoop every night and fed a cod and a shad to the pigeons that cooed from above. Every time she threw a bit of fish to the birds flying around her hair, she'd comment on how sad the pigeons seemed. Although the woman shooed the pigeons away when their numbers grew too big, the neighbors grew tired of the spectacle and they sued the woman. The woman decided to give up the pigeons and pursued her love for golf. Every morning at eight o'clock, she teed off at the first hole. Instead of using a golf cart, however, she traveled from hole to hole on her freshly shod horse named Charlie.
Appendix III Direct Magnitude Estimation - Instruction

I am going to present you, a series of short paragraphs in no particular order produced by different speakers. I am interested in knowing how easy you can understand them - or how intelligible they are to you.

Your task is to indicate how easy you can understand them, by assigning numbers to them. The easier you understand a paragraph, the higher number you would assign to it. The harder you understand a paragraph, the lower number you would assign to it.

You will listen to a series of 40 paragraphs with a 4-second interval between each paragraph. After you have heard the first paragraph, give its intelligibility a number - any number you think appropriate. There will be 4 seconds before the next paragraph is played.

Do not factor in any obvious reading errors when you assign a number to a paragraph.

Try to make the ratios between the numbers you assign to different paragraphs correspond to the ratios between the intelligibility of the paragraphs. For example, if a paragraph is twice as easy to understand than the last one, give a number that is two times the last number. If it’s one fifth as easy to understand, then assign a number that is one fifth to the last number.

Remember, you may assign any number and there is no limit on the number that you assign. There are no right or wrong answers.

Any questions?
### Appendix IV Correlation Matrix for PD

<table>
<thead>
<tr>
<th></th>
<th>Age</th>
<th>AHT</th>
<th>MoCA</th>
<th>M1D.s</th>
<th>M1D.p</th>
<th>Intll</th>
<th>JND_AUD</th>
<th>AOU_AUD</th>
<th>JND_TAC</th>
<th>AOU_TAC</th>
<th>Yr</th>
<th>ADL</th>
<th>ADL-Sp</th>
<th>H&amp;Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>0.41</td>
<td>0.35</td>
<td>-0.11</td>
<td>-0.16</td>
<td>-0.05</td>
<td>0.12</td>
<td>0.44</td>
<td>0.35</td>
<td>-0.09</td>
<td>0.11</td>
<td>-0.21</td>
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<td>-0.08</td>
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</tr>
<tr>
<td>AHT$^a$</td>
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<td>-0.38</td>
<td>-0.08</td>
<td>-0.02</td>
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<td>0.36</td>
<td>0.30</td>
<td>0.00</td>
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</tr>
<tr>
<td>MoCA</td>
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<td>0.08</td>
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</tr>
<tr>
<td>M1D.s</td>
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<td>0.28</td>
<td>0.82</td>
<td>0.67</td>
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<td>-0.02</td>
<td>-0.39</td>
<td>-0.72</td>
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<td>0.34</td>
<td>0.35</td>
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<td>M1D.p</td>
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<td>0.10</td>
<td>0.03</td>
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<td>-0.31</td>
<td>-0.31</td>
<td>-0.22</td>
<td>-0.22</td>
<td>0.47</td>
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<tr>
<td>Intll$^d$</td>
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<tr>
<td>JND_AUD</td>
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<td>0.74</td>
<td>0.69</td>
<td>0.96</td>
<td>0.48</td>
<td>0.36</td>
<td>0.12</td>
<td>0.22</td>
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<td>-0.30</td>
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</tr>
<tr>
<td>AOU_AUD</td>
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<td>0.26</td>
<td>0.39</td>
<td>0.78</td>
<td>0.74</td>
<td>0.49</td>
<td>0.34</td>
<td>0.05</td>
<td>0.28</td>
<td>-0.17</td>
<td>0.55</td>
<td></td>
</tr>
<tr>
<td>JND_TAC</td>
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<td>0.31</td>
<td>0.22</td>
<td>0.02</td>
<td>0.39</td>
<td>0.68</td>
<td>0.55</td>
<td>0.15</td>
<td>0.02</td>
<td>-0.59</td>
<td>-0.10</td>
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<td>AOU_TAC</td>
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<td>0.35</td>
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<td>0.06</td>
<td>0.33</td>
<td>0.97</td>
<td>0.44</td>
<td>0.58</td>
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<tr>
<td>Yr$^c$</td>
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<td>0.54</td>
<td>0.24</td>
<td>0.40</td>
<td>0.89</td>
<td>0.07</td>
<td>0.21</td>
<td>0.61</td>
<td>0.09</td>
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<tr>
<td>ADL$^f$</td>
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<td>0.07</td>
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<tr>
<td>ADL-Sp</td>
<td>$^g$</td>
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<td>0.70</td>
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<tr>
<td>H&amp;Y$^h$</td>
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<td>0.62</td>
<td>0.39</td>
<td>0.39</td>
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</tbody>
</table>

$^a$ Upper right half shows correlation coefficients; lower left half shows $p$-values. All values are based on two-tailed tests.

$^b$ AHT = absolute hearing threshold. $^c$ M1D.s = sentence M1D. $^d$ M1D.p = passage M1D. $^e$ Intll = intelligibility scores. $^f$ Yr = years post-diagnosis. $^g$ ADL = UPDRS-ADL scores. $^h$ ADL-Sp = UPDRS-ADL scores for speech.
Appendix V Correlation Matrix* for HC

<table>
<thead>
<tr>
<th></th>
<th>Age</th>
<th>AHT</th>
<th>MoCA</th>
<th>M1D.s</th>
<th>M1D.p</th>
<th>Intll</th>
<th>JND_AUD</th>
<th>AOU_AUD</th>
<th>JND_TAC</th>
<th>AOU_TAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
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<td>0.08</td>
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<td>-0.50</td>
<td>-0.22</td>
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</tr>
<tr>
<td>MoCA</td>
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<td>0.14</td>
<td>-0.66</td>
<td>-0.47</td>
<td>-0.30</td>
<td>-0.57</td>
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</tr>
<tr>
<td>M1D.s</td>
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<td>0.29</td>
<td>0.85</td>
<td>0.68</td>
<td>0.22</td>
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<td>0.04</td>
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</tr>
<tr>
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<td>0.01</td>
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<tr>
<td>AOU_AUD</td>
<td>0.88</td>
<td>0.14</td>
<td>0.17</td>
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<td>0.45</td>
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<tr>
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<td>0.93</td>
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<td>0.05</td>
<td>0.25</td>
<td>0.20</td>
<td></td>
</tr>
</tbody>
</table>

* Upper right half shows correlation coefficients; lower left half shows p-values. All values are based on two-tailed tests.

a AHT = absolute hearing threshold. b M1D.s = sentence M1D. c M1D.p = passage M1D. d Intll = intelligibility scores.
Appendix VI Probability Density Plots for M1 of /s/ and M1 of /ʃ/
* HC01-05 were women and HC06-10 were men.