Research Article

Tongue- and Jaw-Specific Articulatory Underpinnings of Reduced and Enhanced Acoustic Vowel Contrast in Talkers With Parkinson's Disease

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Purpose: This study sought to identify the articulator-specific mechanisms that underlie reduced and enhanced acoustic vowel contrast in talkers with dysarthria due to Parkinson's disease (PD).

Method: Seventeen talkers with mild–moderate dysarthria due to PD and 17 controls completed a sentence repetition task using typical, slow, loud, and clear speech. Tongue and jaw articulatory movements were recorded using 3D electromagnetic articulography. Independent tongue displacements, jaw displacements, and acoustic vowel contrast were calculated for the diphthong /aɪ/ embedded in the word *kite*.

Results: During typical speech, independent tongue displacement, but not jaw displacement, contributed significantly to the intertalker variance in acoustic vowel contrast. Loudness-related acoustic vowel contrast gains

were predominantly jaw driven in controls but driven by the tongue and jaw in talkers with PD. Further, in both groups, clarity-related acoustic vowel contrast gains were predominantly jaw driven. Finally, in both groups, rate-related acoustic vowel contrast gains were predominantly tongue driven; however, the jaw also contributed. These jaw contributions were greater in the PD group than in the control group.

Conclusions: Findings suggest that a tongue-specific articulatory impairment underlies acoustic vowel contrast deterioration in talkers with PD, at least during the early stages of speech decline. Findings further suggest that slow speech engages the impaired tongue more than loud and clear speech in talkers with PD. However, slow speech was also associated with an abnormally strong jaw response in these talkers, which suggests that a compensatory articulatory behavior may also be elicited.

Parkinson's disease (PD) is a neurodegenerative disease commonly associated with a progressive impairment of motor functions. Cardinal motor symptoms include a resting tremor, slowed movements (bradykinesia), reduced movements (hypokinesia), muscle stiffness (rigidity), and postural instability (e.g., Jankovic, 2008). In addition to progressively impaired limb motor functions (e.g., walking, writing, reaching, and grasping),

bulbar motor functions (e.g., speaking, swallowing) can also become affected. In fact, up to 90% of people with PD develop dysarthria (e.g., Ho, Iannak, Marigliani, Bradshaw, & Gates, 1998; Logemann, Fisher, Boshes, & Blonsky, 1978). The deterioration of speech function is characterized by pathological changes in speech breathing, vocal quality, vocal loudness, speaking rate, prosody, and speech sound precision; however, the extent to which these pathological changes manifest can vary greatly among talkers with PD (e.g., Darley, Aronson, & Brown, 1969; Dromey, Ramig, & Johnson, 1995; Duffy, 2013; Flasskamp, Kotz, Schlegel, & Skodda, 2012; Huber & Darling, 2011; Logemann et al., 1978; Skodda, Rinsche, & Schlegel, 2009; Solomon & Hixon, 1993).

Within the articulatory subsystem, hypokinesia manifests as reduced articulatory displacements of the jaw, lips, and tongue (e.g., Ackermann, Hertrich, Daum, Scharf, & Spieker, 1997; Caligiuri, 1989; Connor, Abbs, Cole, & Gracco, 1989; Forrest & Weismer, 1995; Forrest, Weismer, & Turner, 1989; Hirose, Kiritani, Ushijima, & Sawashima, 1978; Kearney et al., 2017; Mefferd, 2015; Weismer,

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Yunusova, & Bunton, 2012; Yunusova, Weismer, Westbury, & Lindstrom, 2008; but see Wong, Murdoch, & Whelan, 2010, 2011). Acoustically, a reduced vowel contrast has been frequently reported for talkers with PD (e.g., contracted acoustic vowel space area, reduced formant transition extents) and is thought to reflect hypokinesia within the articulatory subsystem (e.g., Forrest et al., 1989; Kim & Choi, 2017; Mefferd, 2015; Skodda, Grönheit, & Schlegel, 2012; Skodda, Visser, & Schlegel, 2011; Tjaden, Lam, & Wilding, 2013; Tjaden & Wilding, 2004; Walsh & Smith, 2012; J. A. Whitfield & Goberman, 2014). The deterioration of acoustic vowel contrast can, in part, explain the speech intelligibility loss that occurs as speech motor function declines in talkers with PD (e.g., Kim, Kent, & Weismer, 2011; McRae, Tjaden, & Schoonings, 2002; Weismer, Jeng, Laures, Kent, & Kent, 2001). However, despite its well-known contribution to speech intelligibility, our understanding of the articulator-specific mechanisms that underlie reduced acoustic vowel contrast in talkers with PD remains incomplete. Specifically, it is currently unclear if the disease affects all articulators equally or if displacements of one articulator are disproportionately more affected than others in these talkers.

One reason for the limited insights in articulator-specific contributions to reduced acoustic vowel contrast in talkers with PD is the lack of speech kinematic studies that examine tongue displacements separately from those of the jaw. Instead, most kinematic studies on talkers with PD provided findings for tongue composite displacements, that is, tongue movements that also include the contributions of the jaw (e.g., Forrest & Weismer, 1995; Forrest et al., 1989; Hirose et al., 1978; Kearney et al., 2017; Weismer et al., 2012; Wong et al., 2010, 2011). To our knowledge, only one study is currently available that specifically reported jaw displacements and tongue displacements after they were decoupled from the jaw (Yunusova et al., 2008). Study outcomes suggest that these independent tongue displacements are differentially more impaired than those of the jaw in talkers with PD. The kinematic measures were, however, not linked to vowel acoustic measures to directly test the associative strength between the magnitude of tongue and jaw displacements and vowel acoustics in these talkers.

Studies that have linked kinematic and speech perceptual measures also support the notion that an impaired tongue function underlies the speech decline in talkers with PD. In these studies, jaw displacements either did not vary predictably with perceived speech severity ratings (Forrest et al., 1989) or showed weaker associations with speech intelligibility scores than tongue composite displacements in talkers with PD (Kearney et al., 2017). Furthermore, Logeman et al. (1978) proposed that articulatory movements of the posterior tongue deteriorate before those of the anterior tongue and lips based on phonemic error patterns that were observed in these talkers. However, because of the anatomical coupling of the tongue and lips with the jaw, this analysis did not allow insights in the extent to which a jaw motor impairment may have also contributed to the perceived speech errors. A similar limitation also exists for

findings of strong associations between reduced tongue composite displacements and reduced acoustic vowel contrast in talkers with PD (Mefferd, 2015). Because the recorded tongue composite displacements were not decoupled from the jaw in this study, it currently remains unclear (a) if jaw displacements were reduced and negatively impacted the tongue composite displacements; (b) if independent tongue displacements were reduced, but jaw displacements were unaffected by the disease; or (c) if a general downscaling of both, jaw and independent tongue displacements, resulted in reduced tongue composite displacements in these talkers.

Although overall changes in vocal tract configurations are most relevant for the speech acoustic signal and speech intelligibility, insights in each articulator's contribution to vocal tract changes are also critical. From a theoretical perspective, insights in articulator-specific contributions to vocal tract and speech acoustic changes can provide empirical evidence for current models of typical and disordered speech production. Clinically, such insights can help identify the articulator that contributes most to speech acoustic deviances, which in turn can negatively impact speech intelligibility. Presumably, acoustic vowel contrast and speech intelligibility should improve when this articulator is specifically targeted in therapeutic interventions.

Currently, rate reduction (slow speech), loudness manipulation (loud speech), and speech clarity manipulation (clear speech) are speech behavioral treatment approaches that are recommended for talkers with PD (Yorkston, Hakel, Beukelman, & Fager, 2007). Although each speech cue only addresses one specific aspect of speech (i.e., rate, loudness, speech imprecision), they are considered global speech behavioral modifications because they can affect segmental as well as suprasegmental aspects of speech and elicit widespread changes across all speech subsystems (e.g., Dromey & Ramig, 1998; Patel, Connaghan, & Campellone, 2013; Tjaden, Sussman, & Wilding, 2014). It is particularly important to understand how speech behavioral modifications impact articulatory behavior because articulatory deficits have been shown to contribute most to speech intelligibility loss (De Bodt, Hernández-Díaz Huici, & Van De Heyning, 2002; Lee, Hustad, & Weismer, 2014). It is also important to understand the differential effect of loud, slow, and clear speech on articulatory behavior in talkers with PD to establish a scientific basis for the selection of a specific speech treatment for an individual with PD. That is, several studies documented a positive effect of slow, loud, and clear speech cues on articulatory movements, acoustic vowel contrast, as well as speech intelligibility in talkers with PD (e.g., Darling & Huber, 2011; Dromey, 2000; Dromey & Ramig, 1998; Kearney et al., 2017; Mefferd, 2015; Sapir, Spielman, Ramig, Story, & Fox, 2007; Sauvageau, Roy, Langlois, & Macoir, 2015; Tjaden et al., 2013, 2014; Tjaden & Wilding, 2004; J. Whitfield, Dromey, & Palmer, 2018). However, direct comparisons across these three speech cueing techniques revealed that the positive effect on acoustic vowel contrast was greater during clear and slow speech than during loud speech in talkers with PD (Tjaden et al., 2013). Further, the extent to which perceived speech severity

improved was greater during clear and loud speech than during slow speech in these talkers (Tjaden et al., 2014).

Side-by-side comparison of the articulatory mechanisms that underlie the cueing-related improvements in acoustic vowel contrast and speech intelligibility can further strengthen the rationale for a specific treatment selection. For example, to directly target the articulator that contributes most to the deteriorating acoustic vowel contrast and speech intelligibility loss, the speech modification that predominantly engages the impaired articulator can be selected. Indeed, a recent side-by-side comparison of slow, loud, and clear speech effects on articulatory behavior showed that the articulatory response patterns of the tongue and jaw varied systematically with these speech modification cues in healthy talkers (Mefferd, 2017). Specifically, slow speech elicited significantly larger independent tongue displacements than clear and loud speech, and the increase in independent tongue displacements predominantly accounted for the rate-related gains in vowel acoustic contrast. By contrast, clear and loud speech elicited a general upscaling of jaw and independent tongue movements. During clear speech, both articulators also contributed to acoustic vowel contrast gains, whereas during loud speech, gains in acoustic vowel contrast were mostly tongue driven.

Such detailed understanding about the articulator-specific mechanisms that underlie cueing-related improvements in acoustic vowel contrast is still lacking for talkers with PD. So far, only one kinematic study is available that conducted a side-by-side comparison of these speech modification effects on jaw and tongue composite movements in talkers with PD (Kearney et al., 2017). Jaw and tongue composite movement sizes were measured based on sentence-length movement trajectories. Study outcomes showed that, in talkers with PD, loud speech elicited the largest gains in jaw displacements followed by clear speech and then slow speech. By contrast, task effects did not yield any significant differences for tongue composite displacements in both groups of talkers. That is, tongue composite displacements increased to similar extents from typical speech to loud, slow, and clear speech. These observed cueing effects on jaw and tongue composite displacements suggest that independent tongue displacements may vary predictably with speech cues in talkers with PD.

The purpose of the current study was twofold. The first aim was to delineate tongue- and jaw-specific articulatory mechanisms that underlie reduced acoustic vowel contrast in talkers with PD. The second aim of this study was to delineate tongue- and jaw-specific articulatory mechanisms that underlie enhanced acoustic vowel contrast in talkers with PD. That is, the study sought to examine the effect of speech modifications (slow, loud, clear speech) on jaw displacement, independent tongue displacement, and acoustic vowel contrast and further aimed to determine the extent to which jaw and independent tongue displacements contributed to the change in acoustic vowel contrast in response to these speech modification cues. Specific research hypotheses were not formulated for these two aims because of the limited number of studies on decoupled tongue and jaw displacements

at the segmental level in talkers with PD. However, with regard to acoustic vowel contrast, it was predicted that talkers with PD would achieve significantly greater acoustic vowel contrast gains in response to clear and slow speech than in response to loud speech and that overall acoustic vowel contrast would be smaller in talkers with PD than in control talkers (e.g., Mefferd, 2017; Tjaden et al., 2013).

Method

Participants

Seventeen talkers with PD (nine men, eight women) and 17 controls (nine men, eight women) were included in this study. The mean age of talkers with PD was 69.1 years (range: 57–84 years). The mean age of the control group was 68.3 years (range: 53–85 years). Six talkers with PD and eight controls spoke with a Standard American English dialect, nine talkers with PD and seven controls spoke with a subtle regional dialect, and two talkers with PD and two controls spoke with a prominent regional dialect. Table 1 presents the demographics for the talkers with PD and a variety of speech perceptual measures. Speech perceptual characteristics of the talkers with PD were provided by a speech-language pathologist with expertise in motor speech disorders based on the perceptual dimensions established by Darley et al. (1969). The speech-language pathologist was aware of the clinical diagnosis.

The Sentence Intelligibility Test (SIT; Yorkston, Beukelman, Hakel, & Dorsey, 2007) was further used to index speech severity. Undergraduate students without background in speech-language pathology orthographically transcribed the SIT sentences. A research assistant checked the transcriptions and verified that the intelligibility score did not result from typographical errors or the talker misreading or omitting any words. Two SIT scores were obtained for each SIT recording. SIT scores were averaged. Further, speaking rate was calculated for all talkers with PD based on the SIT sentences.

In this study, the following exclusion criteria were applied: (a) scoring less than 25 points on the Mini-Mental State Examination (Folstein & Folstein, 2012); (b) wearing hearing aids or having a prescription for hearing aids; (c) a self-reported history of a speech, language, or hearing impairment unrelated to PD (e.g., dysphonia due to vocal fold paralysis); (d) a self-reported history of neurological diseases other than PD (e.g., stroke); (e) a history of neurosurgical treatment (e.g., deep brain stimulation); (f) severe disease-related speech dysfluencies; (g) the absence of any perceivable speech abnormalities in talkers with PD as judged by the certified speech-language pathologist based on the SIT recordings; and (h) the presence of an Inland Southern dialect, a subdialect of the Southern American English dialect (reasons explained under the Experimental Tasks section).

The completion or enrollment in speech treatment programs was not an exclusion criterion for talkers with PD. One talker with PD was enrolled in speech therapy at the time of the data collection and had completed an

Table 1. Characteristics of talkers with Parkinson's disease (PD).

Talker	Age	Yrs Dx	SIT score	Rate (WPM)	Severity	Speech characteristics
PDM12	72	4	99	220	Mild	Harsh voice, low pitch, reduced stress
PDM13	69	5	95	175	Moderate	Imprecise consonants, phoneme repetitions, fast rate, short rushes of speech, reduced stress, loudness decay
PDM14	84	4	93	224	Mild	Imprecise consonants, harsh voice, reduced stress, monoloudness, monopitch
PDM15	75	4	96	206	Moderate	Imprecise consonants, harsh voice, fast rate, reduced stress, low pitch, monopitch
PDM17	72	12	93	204	Mild	Short rushes of speech, reduced stress, irregular breakdowns, monopitch
PDM19	66	7	97	201	Mild–moderate	Imprecise consonants, short rushes of speech, monopitch, harsh voice, reduced stress, irregular breakdowns
PDM21	73	5	97	188	Mild	Breathy voice, low pitch, monopitch, reduced stress
PDM23	63	15	100	134	Mild	Festinations, breathy voice, low pitch, monoloudness, low volume, reduced stress
PDM24	73	6	99	177	Mild	Harsh voice, breathy voice
PDF10	73	1	95	176	Mild	Harsh voice
PDF11	57	14	97	261	Mild	Imprecise consonants, fast rate, short rushes of speech, reduced stress, low pitch, monopitch, monoloudness, vocal decay, harsh voice, hyponasality
PDF15	74	1	100	197	Mild	Harsh voice, breathy voice, wet voice irregular breakdowns, low pitch
PDF16	61	4	100	242	Mild	Harsh voice, strained-strangled voice, low pitch, monopitch, reduced stress
PDF17	60	4	99	199	Mild	Harsh voice, breathy voice, hyponasality, low pitch, monopitch, monoloudness
PDF18	66	7	99	196	Mild	Harsh voice, voice tremor, wet voice, low pitch
PDF19	70	2	100	202	Mild	Harsh voice, low pitch, monopitch, monoloudness, reduced stress
PDF20	66	5	96	220	Mild	Imprecise consonants, irregular breakdowns, fast rate, short rushes of speech, reduced stress, low pitch, monopitch, reduced loudness, harsh voice, strained-strangled voice

Note. Yrs Dx = years since diagnosis; SIT score = Sentence Intelligibility Test score; WPM = words per minute; PDM = male; PDF = female.

evaluation and one exercise session. Four talkers with PD reported that they had participated in speech treatment previously (2 months to 2 years ago) but had stopped their exercise programs once treatment was completed. All participants with PD were taking antiparkinsonian medication. Data collections were scheduled approximately 1 hr after talkers with PD had taken their medication. One talker with PD used a pump that continuously supplied medication. The timing was chosen to record all talkers when the medication was in full effect, and their performance was representative of how they function most of the time during the day (e.g., Darling & Huber, 2011).

All participants completed a pure-tone hearing screening at 500, 1000, 2000, and 4000 Hz; however, participants were not excluded based on the result of the hearing screening. Twelve talkers with PD and 16 controls completed the hearing screening at 45 dB or better in one ear at 500, 1000, 2000, and 4000 Hz. The remaining five talkers with PD and the one control talker completed the hearing screening at 500 and 1000 Hz with 40 dB HL or better, at 2000 Hz with levels ranging between 45 and 55 dB HL, and at 4000 Hz with levels ranging between 50 and 70 dB HL.

Experimental Tasks

The data for this study were collected as part of a larger research protocol. For the purpose of this study, all participants were instructed to produce the sentence “She saw a boy with a kite hiding behind the house” five times. The tongue and jaw movements as well as the acoustic contrast during the diphthong /aɪ/ in “kite” were of interest.

The word *kite* was particularly well suited because the phonetic context provided reliable diphthong boundaries for acoustic and kinematic analyses. The diphthong was also placed in this specific phonetic context of voiceless stops because talkers with a Southern American English dialect do not monophthongize /aɪ/ when it is followed by a voiceless stop. An exception to this rule is the Inland Southern dialect, which is typically spoken in the Appalachian area (Labov, Ash, & Boberg, 2006).

The order of the rate, loudness, and clarity modulations varied within both groups. To minimize the likelihood of an order effect, participants completed two speech tasks that were unrelated to this project and that required the use of typical speech before moving on to the next speech modification task. The experimenter verified perceptually that each participant completed each speech task as instructed. If necessary, the participant was interrupted and the task was explained again. To elicit a reduced speaking rate, participants were instructed to talk at half their typical speaking rate by stretching their words. To elicit loud speech, participants were instructed to speak about twice as loud as they normally speak. Clear speech was elicited by instructing talkers to overenunciate each word in the sentence, to put effort into their speech production, and to make sure that they produce each word as clearly as possible. Further, the instructions mentioned that, by overenunciating each word, their speech could become slower and/or louder than normal (Mefferd, 2017; Tjaden et al., 2013). The instructions for clear speech were chosen because they elicited the greatest magnitude of vowel acoustic change relative to other instructions previously used (Lam & Tjaden, 2016; Lam, Tjaden, & Wilding, 2012).

Data Collection

Kinematic and acoustic data were recorded in a synchronized fashion using the three-dimensional (3D) electromagnetic articulograph (AG501, Carstens Medizinelektronik GmbH). Kinematic data were sampled at 1250 Hz and then down-sampled to 250 Hz. To record kinematic movements, small sensor coils were attached with dental adhesive (Periacryl 90, GluStitch Inc.) 1–2 cm posterior of the tip of the tongue (tip of the tongue sensor) and 4–5 cm posterior of the tip of the tongue (posterior tongue sensor) at the sagittal midline. Further, to record jaw movements, one to three sensors were attached with putty (Stomaheasive, ConvaTec) to the gumline of the lower incisors. That is, in all cases, one jaw sensor was placed at the sagittal midline (jaw center sensor), and in some cases, two additional jaw sensors were placed near the right and left lower canines. To record upper and lower lip movements, one sensor was placed at midline of the lower lip and one was placed at midline on the upper lip.

All participants wore a pair of goggles with three head sensors attached to the goggles (head center, head right, and head left). These sensors were used to correct speech kinematic data for head movements. Finally, three sensors were placed on the biteplate (provided by Carstens Medizinelektronik GmbH). Each participant was asked to hold a biteplate so that the front incisors aligned with the marking on the bite plane. A short recording at rest was completed during which the participant was asked not to move. Kinematic data were corrected for head movements and transposed into a head-based coordinate system based on the rest recording using NormPos (Carstens Medizinelektronik GmbH). Finally, kinematic data were low-pass filtered at 15 Hz using a customized MATLAB program called *Speech Movement Analysis for Speech and Hearing Research* (SMASH; Green, Wang, & Wilson, 2013).

Data Analysis

The kinematic and acoustic data analyses paralleled those described in Mefferd (2017). That is, in the kinematic domain, the onset and offset of the diphthong were determined based on the movement extrema of the tongue composite movement trajectory in the ventral–dorsal dimension. The 3D position coordinates of the tongue sensor and jaw sensor were extracted at the onset and the offset. The 3D Euclidean distances between the onset and offset positions were calculated for both sensors.

To decouple the tongue composite displacement into the independent tongue displacements (iTongue) and the jaw displacements (jaw_{adj}) during the diphthong /aɪ/, an algorithm was used that considered the observed jaw displacement at the frontal incisors, the jaw's rotational movements, and the distance of the posterior tongue sensor to the anterior location of the jaw sensor. All reported jaw displacements in the article refer to the calculated jaw displacements (jaw_{adj}). This algorithm is described in detail in Mefferd (2017). A linear subtraction of jaw movement

from the tongue composite movement was not possible because it would introduce relatively large errors for iTongue displacements and jaw_{adj} displacement estimates (see Westbury, Lindstrom, & McClean, 2002). Nevertheless, small errors for iTongue and jaw_{adj} displacement estimates are unavoidable. In five instances (all in one talker), the decoupling approach resulted in negative independent tongue displacements ranging from –0.97 to –0.09. These negative independent tongue displacements suggest that the jaw_{adj} displacement may have been overestimated by the decoupling algorithm. However, because these negative independent tongue displacement values were within the reported error range of current decoupling algorithms, they were not omitted from the data set.

The speech acoustic signal was transduced using an omnidirectional condenser lavalier microphone (Audio-technica AT899), amplified using a preamplifier (Tascam US-4x4), and recorded with a sampling rate of 48000 Hz to the hard drive of the control computer of the articulograph. The recording level was set at the beginning of the data collection and was not changed during the data collection. The microphone was positioned outside of the electromagnetic field in front of the participant with a microphone-to-mouth distance of approximately 20–25 cm. The microphone-to-mouth distance was measured for each participant. A 1000-Hz calibration tone was recorded after each data collection using the participant's microphone-to-mouth distance as the distance from the sound source to the microphone and SPL meter (Švec & Granqvist, 2018).

Speech acoustic measures were obtained using TF32 (Milenkovic, 2001). The acoustic signal was displayed as the waveform and the wideband spectrographic view (300–400 Hz) with formant trajectories computed by the linear predictive coding algorithm. The diphthong onset was defined as the first glottal pulse of the diphthong following the release burst of the /k/, and the diphthong offset was defined as the last glottal pulse prior to close for the /t/ in *kite*. During this segment, the second formant (F2) minimum, the F2 maximum, and their corresponding first formant (F1) values were extracted. The Euclidean distance in F1–F2 planar space between the two coordinates [(F2 minimum, corresponding F1) and (F2 maximum, corresponding F1)] was calculated as an index of acoustic vowel contrast (Mefferd, 2015, 2017; Mefferd & Green, 2010). In case of formant tracking errors or missing linear predictive coding tracking, formants were tracked based on the visual inspection of the wideband spectrogram.

Verification of Rate, Loudness, and Clarity Modulation

To verify that talkers reduced their speech rate, movement durations were examined based on defined onset and offset of the tongue movements during the diphthong /aɪ/. Loudness manipulation was verified by measuring vocal intensity using TF32. The waveform display and the wideband spectrographic view in TF32 were used to identify the diphthong boundaries (as defined above). Mean vocal

intensity values were extracted for each diphthong and reexpressed relative to the measured intensity of a calibration tone. Finally, because clear speech is commonly associated with a reduced rate and/or an increased vocal intensity, movement duration and vocal intensity were examined to verify clarity modulation (e.g., Ferguson & Kewley-Port, 2007; Picheny, Durlach, & Braidá, 1986). However, rate and intensity changes were expected to be smaller during clear speech than during slow and loud speech (Tjaden et al., 2013).

Measurement Reliability

To determine intermeasurer reliability, 10% of the acoustic data were reanalyzed by a different person. Results yielded a mean absolute difference in acoustic vowel contrast of 44 Hz ($SD = 36$ Hz). Further, mean absolute difference for the F1 measures was 28 Hz ($SD = 31$ Hz), and for the F2 measures, it was 33 Hz ($SD = 32$ Hz). These intermeasurer reliability results were comparable with those of previous studies (e.g., Tjaden & Wilding, 2004; Weismer et al., 2001).

Statistical Analysis

Data for 19 out of a possible 680 sentence productions were missing due to various reasons (e.g., technical problems with sensor tracking, speech errors such as word substitutions). Normality tests of all dependent measures revealed that the jaw displacement data distribution was positively skewed. Therefore, jaw displacements were log-transformed to normal distribution prior to use in linear modeling. SPSS (Version 25) and STATA (Version 13) were used for the statistical analyses. Unless otherwise noted, a maximum alpha of .05 ($p < .05$) was used for determining statistical significance.

Linear mixed-effects (LME) analyses were used to assess the effects of speech modification on independent tongue displacement, jaw displacement, and acoustic vowel contrast. In these LME analyses, the interaction effect of speech condition (typical, loud, clear, slow speech) and group (control, PD), as well as the main effects of each factor (speech condition, group), were entered as fixed effects. To control for the within-subject effects of the participants, participant ID number was entered as a random effect. If a main effect or an interaction effect was statistically significant, post hoc comparisons were performed using the same LME approach applying Bonferroni adjustments to the critical alpha value to maintain a maximum Type I error rate of .05.

To assess the relative contributions of the tongue and the jaw to reduced and enhanced acoustic vowel contrast, a series of linear regressions of independent tongue displacement and jaw displacement on acoustic vowel contrast was used. Both kinematic variables (independent tongue displacements and jaw displacements) were submitted as independent variables; acoustic vowel contrast was submitted as the dependent variable. Due to each participant producing

five repetitions for each speech condition, the standard errors used to generate the probabilities of statistical significance were adjusted for the participant clusters (STATA “cluster” option on the “regress” command). In addition to extracting the statistical significance of each of the two standardized beta coefficients resulting from these linear regression analyses, standardized beta coefficients were squared to describe the percentage of variance in acoustic vowel contrast that was associated with the variance in each specific articulator.

To specifically address the first research aim (i.e., articulator-specific underpinnings of reduced acoustic vowel contrast), a linear regression analysis was conducted on the data set associated with typical speech only. To address the second research aim (i.e., articulator-specific underpinnings of enhanced acoustic vowel contrast), a series of linear regressions was conducted on data of typical speech and one of the speech behavioral modifications within each group (i.e., typical + loud, typical + clear, typical + slow). To control for severity-related intertalker variability that could particularly confound the regression analyses in the PD group, each individual’s raw data for the conditions of interest (i.e., typical + loud, typical + clear, typical + slow) were converted into z scores. Those standardized data were submitted to the regressions.

Finally, task performance was verified by submitting each participant’s mean movement duration and mean vocal intensity for each speech condition to separate repeated-measures analysis of variance. Simple comparisons were conducted using independent and paired t tests with Bonferroni corrections of the critical alpha value to maintain a maximum Type I error rate of .05.

Results

Jaw Displacements

Panel A of Figure 1 shows the group means of jaw displacements across speech conditions. A significant Group $\times$ Task interaction was found for jaw displacement, $F(3, 233) = 11.105$, $p < .001$. Post hoc analysis revealed no significant between-group differences for any of the speech conditions; however, typical, clear, and slow speech tended to yield larger jaw displacements in talkers with PD than controls. With regard to within-group effects, pairwise comparisons revealed significantly greater jaw displacements during slow, loud, and clear speech than typical speech ($p < .001$) for both groups. Further, in controls, loud speech elicited significantly greater tongue displacements than slow and clear speech ($p = .002$). In talkers with PD, however, pairwise comparisons revealed significantly greater jaw displacements during clear speech than during loud and slow speech ($p < .009$).

Because some talkers with PD presented with perceived articulatory impairment characterized by articulatory imprecision and an accelerated speech rate and others did not, data of the PD group were further examined by dividing this group into two subgroups based on the presence/absence

Figure 1. Mean jaw displacements (top panels), mean independent tongue displacements (middle panels), and mean acoustic vowel contrast (bottom panels) across speech conditions. Note that jaw displacements (log-transformed) are the calculated jaw displacements (jaw_{adj}) based on the decoupling algorithm (see text for details). PD = Parkinson's disease; PHON/PROS = subgroup with perceived phonatory and prosodic impairments; ARTIC/PHON/PROS = subgroup with perceived articulatory, phonatory, and prosodic impairments.

of a perceptible articulatory impairment. The rationale for dividing the PD group into these two subgroups was that talkers with perceptible articulatory impairments may perform differently from those without articulatory impairments. Thus, Subgroup 1 consisted of nine talkers with perceived phonatory and prosodic impairments and will be referred to as subgroup PHON/PROS (PDF10, PDF15, PDF16, PDF17, PDF18, PDF19, PDM12, PDM21, and PDM24). Subgroup 2 consisted of eight talkers with perceived articulatory, phonatory, and prosodic impairments and will be referred to as subgroup ARTIC/PHON/PROS (PDF11, PDF20; PDM13, PDM14, PDM15, PDM17, PDM19, and PDM23). Due to the small sample size of each subgroup and the exploratory nature of the analyses, subgroup-related findings were examined descriptively.

Panel B of Figure 1 displays the subgroup means of jaw displacements for all four speech conditions. As can be seen, during typical speech, talkers in the PHON/PROS subgroup tended to exhibit larger jaw displacements than controls, whereas jaw displacements of talkers in the ARTIC/PHON/PROS subgroup were comparable to those of controls. During loud speech, jaw displacements of talkers in the PHON/PROS subgroup were comparable to those of controls, whereas jaw displacements of talkers in the ARTIC/PHON/PROS

subgroup were smaller than those of controls. During clear speech, talkers of both subgroups produced larger jaw displacements than controls. Finally, during slow speech, talkers in the PHON/PROS subgroup produced larger jaw displacement than controls, whereas those of talkers in the ARTIC/PHON/PROS subgroup and controls were comparable in size. With regard to task effects, both subgroups displayed similar jaw response patterns. That is, clear speech tended to elicit larger jaw displacements than loud and slow speech.

Independent Tongue Displacements

Panel C of Figure 1 displays the mean independent tongue displacements for talkers with PD and controls across all speech conditions. A significant Group $\times$ Task interaction was found, $F(3, 199) = 8.384, p = .000$. Post hoc analyses revealed no significant between-group differences for any of the speech conditions. With regard to task effects, in both groups, pairwise comparisons revealed that loud, clear, and slow speech were associated with significantly larger independent tongue displacements compared to typical speech ($p \leq .007$). Further, in controls, independent tongue displacements were significantly larger during clear speech than during loud speech ($p = .002$). In talkers with PD, however,

independent tongue displacements were significantly larger during slow speech than during loud and clear speech ($p < .001$).

Panel D of Figure 1 shows the subgroup means for independent tongue movements across all four speech conditions. As can be seen, independent tongue displacements tended to be smaller in talkers of the ARTIC/PHON/PROS subgroup than in controls across all four speech conditions, whereas independent tongue movements of talkers in the PHON/PROS subgroup tended to be larger than those of controls except during clear speech. With regard to task effects, response patterns of the independent tongue displacements differed between the two subgroups. Specifically, independent tongue displacements tended to be larger during loud speech than during clear speech in talkers of the PHON/PROS subgroup, whereas in talkers of the ARTIC/PHON/PROS subgroup, independent tongue displacements tended to be larger during clear speech than during loud speech. However, in both subgroups, slow speech tended to elicit the largest independent tongue displacements.

Acoustic Vowel Contrast

A significant Group $\times$ Task interaction was found for acoustic vowel contrast, $F(3, 235) = 8.930$, $p < .000$. As can be seen in Panel E of Figure 1, acoustic vowel contrast was significantly smaller in talkers with PD than controls during typical speech ($p < .045$). Further, acoustic vowel contrast tended to be smaller in talkers with PD than controls during loud and clear speech, but not during slow speech. Task effects differed between the two groups. Specifically, in talkers with PD, acoustic vowel contrast was significantly larger during clear and slow speech than during loud speech ($p < .001$) and also significantly larger during slow speech than during clear speech ($p = .026$), whereas in controls, acoustic vowel contrast tended to be comparable across loud, slow, and clear speech. The data in Panel F of Figure 1 suggest that, across all speech conditions, talkers in the ARTIC/PHON/PROS subgroup tended to produce smaller acoustic vowel contrasts than controls, whereas talkers in the PHON/PROS subgroup tended to produce larger acoustic vowel contrasts than controls during slow speech. With regard to task effects, both subgroups showed similar patterns.

Articulator-Specific Contributions to Acoustic Vowel Contrast During Typical Speech

Table 2 provides the finding of the collective effects of independent tongue and jaw displacements on acoustic vowel contrast, the standardized beta coefficients and their p values, as well as the percentage of variance in acoustic vowel contrast explained by either independent tongue displacements or jaw displacements. Findings were similar when the data of male and female talkers were analyzed separately. Visual inspection of the raw data (Figure 2, Panel B) suggested that one control (COM23) and one talker with PD (PDM21) differed considerably in their independent tongue displacements relative to their acoustic vowel contrast when compared to all other talkers. After removing these two talkers, independent tongue displacement accounted for 30% of the variance in acoustic vowel contrast. Jaw displacement remained nonsignificant. Further, within the ARTIC/PHON/PROS subgroups, only the tongue was a significant predictor of acoustic vowel contrast (accounting for 31% of variance), whereas within the PHON/PROS subgroup, only jaw displacement was a significant predictor of acoustic vowel contrast (accounting for 29% of the variance) when PDM21 was removed (see Table 2 for details).

Articulator-Specific Contributions to Acoustic Vowel Contrast in Response to Speech Modifications

Loud Speech

Table 3 presents the findings of the mixed-effects regressions for changes from typical to either loud, clear, and/or slow speech. In controls, loudness-related changes in independent tongue displacements accounted for 4% of the variance in acoustic vowel contrast, whereas changes in jaw displacements accounted for 27% of the change in acoustic vowel contrast. In talkers with PD, changes in jaw displacement accounted for 18% of the change in acoustic vowel contrast, whereas changes in independent tongue displacement accounted for 12% of the variance in acoustic vowel contrast. The pattern of jaw- and tongue-specific contributions to changes in acoustic vowel contrast observed for the entire group of talkers with PD remained unchanged when

Table 2. Findings of mixed-effects regressions with independent tongue and jaw displacements as predictor variables of acoustic vowel contrast (typical speech only), standardized beta coefficients of each articulator, and percent variance of acoustic vowel contrast accounted for by independent tongue displacement and jaw displacement.

Variable(s) of interest	All participants	All participants minus COM23 and PDM21	ARTIC/PHON/PROS subgroup	PHON/PROS subgroup minus PDM21
R^2 iTongue + jaw	.16**	.31**	.61**	.37*
iTongue beta coef	.42*	.55**	.56**	-.05
Jaw beta coef	.03	.12	.20	.54*
% iTongue	18	30	31	0
% Jaw	0	1	4	29

Note. COM23 = control talker; PDM21 = talker with PD; iTongue = independent tongue displacement; coef = coefficient; % iTongue = percentage of variance explained by independent tongue displacement; % Jaw = percentage of variance explained by jaw displacement.

* $p \leq .03$. ** $p < .001$.

Figure 2. Scatter plot of jaw displacements (jaw_{adj}) and acoustic vowel contrast (left panel) as well as independent tongue displacement and acoustic vowel contrast (right panel) during typical speech. The gray-shaded circles indicate data of COM23 (filled circles) and PDM21 (open circles). PD = Parkinson's disease; PD PHON/PROS = subgroup of talkers with PD with perceived phonatory and prosodic impairment; PD ARTIC/PHON/PROS = subgroup of talkers with PD with perceived articulatory, phonatory, and prosodic impairment.

talkers with a history of speech therapy and those without a history of speech therapy were analyzed separately as well as when data of the ARTIC/PHON/PROS subgroup and the PHON/PROS subgroup were considered in separate regression analyses.

Clear Speech

As can be seen in Table 3, 29% of the variance in acoustic vowel contrast was accounted for by changes in jaw displacement in controls, whereas 8% of the variance in acoustic vowel contrast was accounted for by changes in independent tongue displacement in controls. In talkers with PD, 44% of the variance in acoustic vowel contrast was accounted for by changes in jaw displacement and 4% of the variance in acoustic vowel contrast was accounted

for by changes in independent tongue displacement. Finally, findings for the entire group of talkers with PD were similar to those revealed when data of each subgroup were submitted to separate regression analyses.

Slow Speech

In controls, 12% of the change in acoustic vowel contrast was accounted for by changes in jaw displacement, whereas 25% of the change in acoustic vowel contrast was accounted for by changes in independent tongue displacement in response to slow speech (see Table 3 for details). In talkers with PD, 18% of the change in acoustic vowel contrast was accounted for by changes in jaw displacement and 27% of change in acoustic vowel contrast was accounted for by changes in independent tongue movement during slow

Table 3. Summary of all mixed-effects regressions with independent tongue and jaw displacements as predictors of acoustic vowel contrast, standardized beta coefficients, percentage of variance accounted for by each articulator, conclusions about the articulator predominantly contributing to the change in acoustic vowel contrast (i.e., "Driver"), and mean change in acoustic vowel contrast for each group.

Variable(s) of interest	Typical-loud		Typical-clear		Typical-slow	
	Controls	PD	Controls	PD	Controls	PD
R^2 iTongue + jaw	.38	.44	.48	.57	.42	.58
iTongue beta coef	.21*	.34	.28	.21	.50	.52
Jaw beta coef	.53	.42	.54	.66	.34	.42
% iTongue	4	12	8	4	25	27
% Jaw	27	18	29	44	12	18
"Driver"	Jaw	Both	Jaw	Jaw	Tongue	Tongue
Contrast gain (Hz)	111	141	197	243	172	305

Note. PD = Parkinson's disease; iTongue = independent tongue displacement; coef = coefficient; % iTongue = percentage of variance explained by independent tongue displacement; % Jaw = percentage of variance explained by jaw displacement; contrast gain = change in acoustic vowel contrast from typical.

* $p = .012$; all other statistical findings were significant at $p \leq .006$.

Table 4. Mean (SD) movement durations and mean (SD) vocal intensities for talkers with Parkinson's disease (PD) and controls.

Group	Speech condition	Movement duration (ms)	Vocal intensity (dB SPL)
Controls	Typical	167.5 (35.1)	69.6 (5.4)
	Loud	175.4 (28.6)	83.3 (5.3)
	Clear	195.6 (39.5)	73.6 (4.9)
	Slow	393.5 (175.7)	70.9 (5.9)
PD	Typical	159.7 (23.9)	71.1 (3.4)
	Loud	159.1 (31.1)	82.5 (4.5)
	Clear	194.9 (73.8)	73.2 (4.9)
	Slow	299.7 (65.4)	71.3 (4.5)

speech. Regressions for each PD subgroup revealed findings that were comparable to those reported for the PD group.

Task Performance

Table 4 provides the group means for movement duration and vocal intensities for talkers with PD and controls across all four speech conditions. A significant task effect on movement duration was found, $F(1.39, 44.61) = 50.633$, $p < .001$. The group effect on movement duration was nonsignificant; however, the Group $\times$ Task interaction yielded a nonsignificant trend, $F(1.39, 44.61) = 3.142$, $p < .07$. In controls, movement durations were significantly longer during slow speech than during typical, loud, and clear speech ($p < .001$). Further, movement durations were significantly longer during clear speech than during loud and typical speech ($p \leq .04$). In talkers with PD, movement durations were only significantly longer during slow speech than during typical, loud, and clear speech ($p < .001$). Finally, during clear and slow speech, controls tended to produce longer movement durations than talkers with PD.

A significant task effect on vocal intensity was found, $F(3, 93) = 110.892$, $p < .001$; however, the group effects and Group $\times$ Task interaction were not significant. Loud speech elicited significantly greater vocal intensities than typical, clear, and slow speech ($p < .001$). Further, vocal intensities during clear speech were significantly greater than those during typical speech ($p = .004$) and slow speech ($p = .013$). For one control talker, the calibration tone was not available to reexpress the recorded intensity levels relative to the calibration tone. However, relative changes in vocal intensities from typical speech to loud speech and from typical speech to clear speech were comparable to the reported group means.

Discussion

This study aimed to delineate the tongue- and jaw-specific underpinnings of reduced and enhanced acoustic vowel contrast in talkers with PD. No specific research hypotheses were formulated due to the limited body of literature on this specific topic. Findings suggest that reduced independent tongue displacements, but not jaw displacements, can partially explain the reduced acoustic vowel contrast in talkers with PD. Further, in both groups, cueing-related gains in acoustic vowel contrast were predominantly jaw driven during clear speech and predominantly tongue driven during slow speech.

Cueing-related gains in acoustic vowel contrast during loud speech were, however, predominantly jaw driven in controls but driven by tongue and jaw in talkers with PD. The following sections will address these main findings in more detail.

Reduced Independent Tongue Displacements Predominantly Account for Reduced Acoustic Vowel Contrast in Talkers With PD, at Least During the Early Stages of Speech Decline

Overall, independent tongue displacements, but not jaw displacements, significantly contributed to acoustic vowel contrast across all talkers. A more detailed subgroup analysis revealed that the association between independent tongue displacement and acoustic vowel contrast was mostly driven by the performance of talkers in the ARTIC/PHON/PROS subgroup. In fact, a follow-up analysis revealed that, within this subgroup of talkers, 31% of the variance in acoustic vowel contrast was accounted for by independent tongue displacement. A tongue-specific articulatory deficit has been suggested previously for the early stages of speech decline in PD. For example, phoneme error patterns in talkers with PD revealed that the most distorted consonants in talkers with PD were those that involved tongue articulation (e.g., velar stops, alveolar fricatives; Logemann et al., 1978). Further, a previous kinematic analysis on talkers with PD suggested that independent tongue displacements were differentially more impaired than those of the jaw, at least in some of the utterances that were examined in this study (Yunusova et al., 2008). The current finding also aligns with the previous observation that tongue composite displacement was a better predictor of speech intelligibility than jaw displacement in talkers with PD (Kearney et al., 2017).

In the current study, jaw displacements of talkers with PD were comparable to those of controls. Previous studies, however, reported significantly reduced jaw displacements in talkers with PD (e.g., Connor et al., 1989; Forrest et al., 1989; Kearney et al., 2017; Walsh & Smith, 2012). Perhaps, talkers with PD in the current study were still at an earlier stage of their speech decline than those in previous studies. A staging of articulatory deterioration has been suggested previously for lip and jaw displacements (Connor et al., 1989) as well as for tongue and lip displacements (Logeman et al., 1978). Examining talkers with a

wider speech severity range may shed more light on the timing of changes in jaw displacements relative to those of the tongue in talkers with PD. It is important to note, however, that jaw displacements can vary tremendously within healthy talkers, which could potentially obscure subtle changes during the early stages of speech decline. A longitudinal approach would therefore provide valuable insights when investigating the timing of articulator-specific changes in talkers with PD.

Although acoustic vowel contrast was significantly smaller in talkers with PD than controls during typical speech, not all talkers with PD who participated in this study demonstrated a reduced vowel contrast during the production of the target utterance. This finding was surprising given previous reports of a reduced acoustic vowel space in talkers with PD even at the subclinical stages of speech decline (e.g., Rusz et al., 2013; Skodda, et al., 2011, 2012). In the current study, all talkers with PD were described as mildly to moderately dysarthric based on their production of the SIT sentences. However, during the sentence repetition task, some talkers with PD produced speech with adequate acoustic vowel contrasts. Previous studies have shown that speech performance of talkers with PD improves during speech tasks with relatively low cognitive-linguistic processing demands (e.g., Bunton & Keintz, 2008; Walsh & Smith, 2012). In this study, a linguistically complex sentence was chosen; however, the nature of the sentence repetition task itself may have not been sufficiently challenging for some talkers with PD.

Preliminary Observations Suggest Different Tongue- and Jaw-Specific Articulatory Profiles for Typical Speech in Talkers in the ARTIC/PHON/PROS Subgroup and Talkers in the PHON/PROS Subgroup

In this study, talkers with PD were subdivided based on their perceptual speech characteristics. The rationale for creating the subgroups was that talkers with a perceptible articulatory impairment may show different articulatory performance patterns than those who do not exhibit a perceptible articulatory impairment. Indeed, talkers of the ARTIC/PHON/PROS subgroup demonstrated reduced independent tongue displacements that predominantly accounted for the deterioration of acoustic vowel contrast during typical speech, whereas talkers of the PHON/PROS subgroup tended to exhibit larger jaw displacements that predominantly accounted for the variance in acoustic vowel contrast within this subgroup. However, these findings should be interpreted cautiously because they are based on a relatively small number of talkers within each subgroup. Nevertheless, the tongue-dominant impairment profile of talkers in the ARTIC/PHON/PROS subgroup aligned with previously reported findings by Yunusova et al. (2008), whereas the jaw-dominant articulatory profile of talkers in the PHON/PROS subgroup may explain findings of abnormally large tongue composite displacements in talkers with PD that have been previously reported by Wong et al. (2010, 2011).

Although underlying reasons for the relatively large jaw displacements of talkers within the PHON/PROS subgroup remain currently unknown, it is worthwhile to consider that disease-related changes within the laryngeal subsystem may elicit changes within the articulatory subsystem. Interactions between the laryngeal and articulatory subsystems have been reported previously in speech kinematic studies investigating articulatory behaviors of talkers with spasmodic dysphonia and may also apply to talkers with PD (Dromey, Nissen, Roy, & Merrill, 2008; Roy, Nissen, Dromey, & Sapir, 2009). Perhaps, talkers of the PHON/PROS subgroup tend to produce larger jaw displacements during this stage of speech decline to promote the radiation of the acoustic energy from the mouth to compensate for deteriorating vocal quality. Future studies are warranted to replicate these preliminary findings and to empirically test interactions between laryngeal and articulatory subsystems in talkers with PD.

Articulator-Specific Mechanisms of Cueing-Related Acoustic Vowel Contrast Gains Differ Between Talkers With PD and Controls

Current findings suggest that articulatory strategies that underlie cueing-related gains in acoustic vowel contrast can differ between talkers with PD and controls. During loud speech, for example, gains in acoustic vowel contrast were jaw driven in controls but tongue and jaw driven in talkers with PD. Particularly, the increase in jaw displacement in response to loud speech is a robust finding in the literature (e.g., Kearney et al., 2017; Mefferd, 2017; Schulman, 1989; Tasko & McClean, 2004). The upscaled jaw displacement is thought to minimize friction noise that may otherwise occur in response to the increased subglottal and supraglottal pressure and airflow (Schulman, 1989). The increase in independent tongue displacement, however, is thought to be an adaptive response to the lowered jaw height during loud speech to ensure adequate vowel acoustics (Schulman, 1989). Alternatively, it has been suggested that loud speech elicits an increase in neuromotor drive that may affect the entire speech motor system (Wohlert & Hammen, 2000), hence an increase in jaw and independent tongue displacement in talkers with PD. In controls, however, jaw displacements, but not independent tongue displacement, increased during loud speech. Potential reasons for such discrepancies may relate to the magnitude of independent tongue displacement of controls during typical speech (see also discussion in the section below). Finally, it is important to point out that the jaw's response to loud speech was weaker in talkers of the ARTIC/PHON/PROS subgroup than in controls and talkers of the PHON/PROS subgroup. This reduced jaw response could be indicative of the onset of a disease-related jaw performance decrement in these talkers.

For clear speech, acoustic vowel contrast gains were jaw driven in both groups; however, the magnitude of the jaw- and tongue-specific displacement changes differed between the two groups. Specifically, talkers with PD tended to exhibit a weaker tongue response and a stronger jaw

response than did controls during clear speech. A similar pattern was observed for slow speech. That is, although in both groups acoustic vowel contrast gains were tongue driven, jaw displacements were larger in talkers with PD than in controls, particularly in the PHON/PROS subgroup. In other clinical groups, for example, in talkers with amyotrophic lateral sclerosis, abnormally large jaw displacements are thought to serve as an articulatory strategy to compensate for impaired independent tongue displacements (e.g., Lee, Bell, & Simmons, 2018; Shellikeri et al., 2016; Yunusova et al., 2008). It is possible that the jaw also served in such a compensatory role for talkers of the ARTIC/PHON/PROS subgroup, particularly during clear speech task. Talkers of the PHON/PROS subgroup, however, did not exhibit a tongue-specific impairment. In fact, the magnitude of change in independent tongue displacements tended to be larger in the PHON/PROS subgroup than in the control group during slow speech. In a follow-up study, individual tongue- and jaw-response patterns to clear and slow speech should be evaluated to shed more light on the role of the jaw during speech production in talkers with PD.

Articulator-Specific Mechanisms of Acoustic Vowel Contrast Gains May Differ Between Younger and Older Typical Adult Talkers

Although current findings for slow speech were congruent with those reported previously, findings for clear and loud speech did not align with previous reports on typical talkers (Mefferd, 2017). One reason for the incongruences may be related to the age of the talkers in the two studies. The previous study focused on young adult talkers, whereas the current study enrolled older talkers. For example, during typical speech, older talkers produced the diphthong /aɪ/ with independent tongue displacements that were twice as large as those produced by younger talkers. By contrast, jaw displacements were comparable between the two groups. It may not be physically possible for older adults to increase independent tongue displacements to the same extent as younger adults in response to speech behavioral cues. In other words, the relatively large independent tongue displacements of older talkers during typical speech may explain (a) why loudness-related gains in acoustic vowel contrast were predominantly jaw driven in older adult talkers but tongue driven in younger adults, (b) why clarity-related gains in acoustic vowel contrast were predominantly jaw driven in older adults but tongue and jaw driven in younger adults, and (c) why independent tongue displacements accounted for a smaller proportion of the gain in acoustic vowel contrast during slow speech in the current study compared to the previous one.

Current Findings for Speech Modification Effects on Speech Kinematics and Speech Acoustics Partially Aligned With Those of Previous Studies

Loud speech elicited significantly larger jaw displacements than clear and slow speech in controls, a finding

that aligned with the trend observed by Kearney et al. (2017). However, in the current study, jaw displacements of talkers with PD were significantly larger during clear speech than during loud and slow speech, whereas Kearney et al. observed significantly larger jaw displacements during loud speech than during slow and clear speech in their group of talkers with PD. The discrepant findings may be explained by the difference in the instructions to elicit clear speech in talkers with PD. It has been shown that instructions to overenunciate yield greater gains in acoustic vowel contrast and speech intelligibility than other types of clear speech instructions (Lam & Tjaden, 2016; Lam et al., 2012; Lam & Tjaden, 2013). It is therefore possible that instructions to overenunciate may have elicited a stronger jaw response in talkers with PD than instructions to speak as if in a noisy environment. Furthermore, differences in the speech materials and differences in the kinematic measurement approach could have also contributed to incongruent findings.

With regard to speech modification effects on acoustic vowel contrast, observed findings were generally in line with the predicted task and group effects and replicated findings by Tjaden et al. (2013) and Mefferd (2017). However, in the study by Tjaden et al., which focused on monophthongs, clear speech elicited greater gains in acoustic vowel contrast than slow speech. By contrast, gains in acoustic vowel contrast were comparable for slow and clear speech in the current study with the diphthong /aɪ/ being examined. Differences in the measurement approach for monophthongs versus diphthongs may explain the discrepant finding. For example, in monophthongs, the midpoint of the vowel is typically used to extract formants, whereas in diphthongs, formant measures are extracted near the onset and offset. The midpoint of the monophthong has been shown to be less sensitive to speaking rate changes than the onset and offset of a monophthong (Gay, 1978), whereas in diphthongs, the offset is most sensitive to speaking rate changes (Gay, 1968).

Clinical Implications and Future Directions

Clear, slow, and loud speeches are currently recommended as speech behavioral treatment approaches to improve the speech of talkers with PD. All three approaches have been shown to yield a positive impact on articulatory behavior and vowel acoustics in typical talkers as well as talkers with dysarthria (e.g., Darling & Huber, 2011; Dromey, 2000; Dromey & Ramig, 1998; Kearney et al., 2017; Lam & Tjaden, 2016; Mefferd, 2015; Sapir et al., 2007; Sauvageau et al., 2015; Tjaden et al., 2013; J. A. Whitfield & Goberman, 2014). Further, loud and clear speech have been shown to improve speech intelligibility and/or speech severity ratings for talkers with PD, whereas results for slow speech have been more variable (e.g., Neel, 2009; Tjaden et al., 2014). Knowledge about the articulator-specific mechanisms that underlie these cueing-related acoustic contrast and speech perceptual gains may help guide the selection of a specific speech modification approach.

Findings for loud, clear, and slow speech suggest that slow speech engages the tongue more than loud and clear speech. However, slow speech can also elicit an abnormally strong jaw response in talkers with PD, which suggests that this speech modification may also train compensatory articulatory behavior in these talkers. When considering the articulator-specific response patterns of each PD subgroup, slow speech appears to target independent tongue displacements quite well in talkers with PD who exhibit perceptible articulatory impairments. One needs to keep in mind, however, that the implementation of a slow speech strategy is known to be difficult for these talkers and may not yield a beneficial effect on speech intelligibility (Tjaden et al., 2014). Clear and loud speech, by contrast, have been shown to elicit more consistent improvements in speech intelligibility than slow speech (Tjaden et al., 2014). Unfortunately, both speech modifications elicited significantly smaller independent tongue displacement than slow speech and therefore may not target independent tongue displacement as effectively as slow speech. Future research studies should investigate if talkers with PD can increase independent tongue displacements during speech when explicitly asked to do so. Comparisons between direct cues (e.g., “Move your tongue more during speech”) and indirect cues (e.g., “Overenunciate and speak as clearly as possible”) could provide insights in the effectiveness of current global speech behavioral treatment approaches relative to those involving more explicit instruction for articulator-specific behavior. Future studies should also determine if and at what stage of speech decline a strong jaw response may be desirable for talkers with PD given previous reports of reduced jaw displacements in talkers with PD (e.g., Forrest et al., 1989). Such insights would provide support for the selection of clear speech as a speech behavioral treatment approach because it elicited the strongest jaw response of all three speech cues and was shown to yield beneficial effects on speech intelligibility in talkers with PD.

Finally, it should be noted that cueing-related articulatory response patterns were highly variable within talkers with PD and controls indicating that group findings of the current study may not necessarily apply to all talkers with PD. Indeed, individual differences in cueing-related articulatory and acoustic response patterns are well known and have been documented previously for talkers with PD (e.g., Sapir et al., 2007; Tjaden et al., 2013, 2014; Wong, Kuruvilla-Dugdale, & Ng, 2017). Efforts to identify more homogeneous subgroups based on speech perceptual characteristics revealed important differences in tongue- and jaw-specific articulatory performance patterns; however, within-subgroup variability remained fairly high. Therefore, future research efforts should be directed toward the identification of variables that can predict the response patterns of talkers with PD.

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