Sentence-Level Movements in Parkinson's Disease:

Loud, Clear, and Slow Speech

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Abstract

Purpose: To further understand the effect of Parkinson's disease (PD) on articulatory movements in speech and to expand our knowledge of therapeutic treatment strategies, this study examined movements of the jaw, tongue blade, and dorsum during sentence production with respect to speech intelligibility, and compared the effect of varying speaking styles on these articulatory movements.

Method: Twenty-one speakers with PD and 20 healthy controls produced three sentences under normal, loud, clear, and slow speaking conditions. Speech intelligibility was rated for each speaker. A 3D electromagnetic articulograph tracked movements of the articulators. Measures included articulatory working spaces, ranges along the first principal component, average speeds, and sentence durations.

Results: Speakers with PD demonstrated a significant reduction in jaw movements as well as shorter than normal sentence durations. Between-speaker variation in movement size of the jaw, tongue blade, and tongue dorsum was associated with speech intelligibility. Analysis of speaking conditions revealed similar patterns of change in movement measures across groups and articulators; larger than normal movement sizes and faster speeds for loud speech; increased movement sizes for clear speech; and larger than normal movement sizes and slower speeds for slow speech.

Conclusions: Sentence-level measures of articulatory movement are sensitive to both disease-related changes in PD and speaking style manipulations.

Keywords: Parkinson's disease, electromagnetic articulography, articulatory working space, movement speed.

Parkinson's disease (PD) is a progressive neurodegenerative disease affecting voluntary movements, including those of the jaw, face, lips, and tongue, during speech and non-speech tasks (Schulz & Grant, 2000). Up to 90% of patients develop a speech disorder, most commonly hypokinetic dysarthria, as the disease progresses (Ho, Iansek, Marigliani, Bradshaw, & Gates, 1998). In addition to the abnormalities in the phonatory and prosodic domains, 45% of patients show difficulties with speech articulation including imprecise consonants and short rushes of speech (Logemann, Fisher, Boshes, & Blonsky, 1978). As a consequence, speech intelligibility becomes reduced, and patients experience loss of communication abilities and social isolation (Pinto et al., 2004).

Kinematic studies provide a direct insight into the articulatory changes in PD. Early studies of jaw and lip movement showed a reduction in movement size and speed as well as impaired duration at the segmental (opening/closing gestures) level (Ackermann, Gröne, Hoch, & Schönle, 1993; Ackermann, Konczak, & Hertrich, 1997; Connor, Abbs, Cole, & Gracco, 1989; Forrest & Weismer, 1995; Forrest, Weismer, & Turner, 1989; Yunusova, Weismer, Westbury, & Lindstrom, 2008). Impaired articulation is, however, more likely to occur in connected speech in PD than at the word or syllable level (Kempler & Van Lancker, 2002; Weismer et al., 2001) and, therefore, the examination of articulation at the sentence level is required. Movements of jaw and lips at the sentence level have been reported, to the best of our knowledge, in a single study of patients with PD and showed a reduction in the ranges of jaw/lip motion and velocity (Walsh & Smith, 2012). Considerably less is known about tongue movements in this population, and existing studies have reported inconsistent findings. Increased tongue movement amplitude and speed were found in studies of opening/closing gestures (Wong, Murdoch, & Whelan, 2010; Wong, Murdoch, & Whelan, 2011), while a study of the tongue tip and dorsum during a passage reading task showed an overall reduction in tongue movement size and speed (Weismer et al., 2012). Further, reports of sentence durations have varied within and across studies, with observations of shorter and comparable to normal durations for speakers with PD (Flint, Black, Campbell-Taylor, Gailey, & Levinton, 1992; McAuliffe, Ward, & Murdoch, 2006; Weismer, Jeng, Laures, Kent, & Kent, 2001).

Measures of articulatory kinematics have rarely been examined in relation to speech intelligibility, yet acoustic studies suggest, albeit indirectly, that speech intelligibility may be related to the extent of articulatory movement impairment in PD (Y. Kim, Kent, & Weismer, 2011; McRae, Tjaden, & Schoonings, 2002). Two studies — one reporting speech kinematics at the segmental level and one at the passage level — have reported associations between articulatory movement measurements and intelligibility in PD. Specifically, Forrest et al. (1989) examined changes in lower lip amplitude and velocity as a function of intelligibility between more and less affected individuals and found smaller movement and reduced velocity in more affected speakers. The findings were based only on three speakers with mild and three speakers with severe intelligibility deficits and, thus, might be limited in their generalizability. More recently, a positive correlation between scaled intelligibility and average speed of the tongue, but not the jaw or lips, during a passage reading task was reported for speakers with PD (Weismer et al., 2012). Assessing the relationship between speech intelligibility and articulatory movement is important in order to identify key movement parameters that contribute to impaired communication in hypokinetic dysarthria.

Most kinematic studies to date report findings related to a single stimulus, which limits the interpretation of findings as well as the generalizability of results. Further, the effect of PD on articulatory kinematics may vary based on the stimulus examined. Stimulus effects have been observed at the acoustic level (Kent et al., 1992; Yunjung Kim, Weismer, Kent, & Duffy, 2009); for kinematic parameters (Yunusova et al., 2008); and in terms of sentence durations (Flint et al., 1992; Weismer et al., 2001). For example, words with larger F2 slopes (Yunjung Kim et al., 2009) and movement extents (Yunusova et al., 2008) appeared to be more sensitive to dysarthria that those with smaller slopes and extents. Certain sentences also appeared to be more sensitive to durational changes in dysarthria than other sentences (Flint et al., 1992; Weismer et al., 2001). In the current study, we examined three different sentences that were designed to elicit large articulatory movements.

Adjusting speaking style, such as increasing loudness or clarity, is a frequently used approach in the treatment of dysarthria (Hustad & Weismer, 2007). These adjustments are applied across utterances and aim to address impairments across multiple physiological subsystems, including respiration, phonation, articulation, and resonance simultaneously (Dromey & Ramig, 1998). The resulting changes, particularly those that occur in the articulatory subsystem, are currently not well understood. Although a number of studies evaluated the effect of loud, clear, or slow speaking styles on jaw and lip movements at the segmental level in PD (Darling & Huber, 2011; Dromey, 2000; Kleinow, Smith, & Ramig, 2001), limited and inconsistent results are available for the tongue (Goozée, Shun, & Murdoch, 2011; Wong, Kuruvilla-Dugdale, & Ng, 2016). Both loud and clear speech in PD were characterized by an increase in movement size and velocity (Darling & Huber, 2011; Dromey, 2000); however, clear speech has also been shown to increase spatiotemporal variability when examined across sentence repetitions (Dromey, 2000). An increase in lip movement variability was also reported for individuals with PD during slow speech, but measures of movement size or speed have not been examined (Kleinow et al., 2001). When compared to control speakers, individuals with PD seem to use different control strategies to vary their speaking style (Darling & Huber, 2011; Goozée et al., 2011). For example, in a study of tongue movements during opening/closing gestures, speakers with PD depended on increasing their velocity during loud speech, in contrast to control speakers who increased their velocity, acceleration, as well as, distance traveled (Goozée et al., 2011). Among limitations of the published research are the emphasis on opening/closing gestures at the segmental level, the focus on relatively mild speakers or those without dysarthria, limited speech material, and limited conditions analyzed for the same group of speakers.

The overall goal of the current study was to examine the effect of speech intelligibility and speaking conditions on articulatory movements of the jaw and tongue during sentences produced by speakers with PD and healthy controls. Participants within the PD group were recruited to represent a broad range of speech intelligibility. The following research questions were addressed:

1) How do sentence-level jaw and tongue movements differ between speakers with PD and healthy controls in the normal speaking condition, and is the articulatory movement variation across speakers with PD associated with variation in their speech intelligibility?
2) What are the effects of loudness, clarity, and rate manipulations on articulatory movements, and are there differences in how the two speaker groups perform in different speaking conditions?

Based on previous literature, we hypothesized that group differences would be observed in jaw and tongue movements during sentences and that movement measures would vary systematically with speech intelligibility. Furthermore, we expected that speaking conditions would elicit changes in articulatory movements for both groups; however, the degree of change in measures of movement size and speed may vary by group.

Methods

Participants

Twenty-one adults diagnosed with PD (M/F = 16/5) and a control group of 20 healthy adults (M = F) were recruited for the study. Participant demographic and clinical characteristics are presented in Table 1. All speakers completed the Montreal Cognitive Assessment (MoCA) (Nasreddine et al., 2005), passed a vision screening, and had pure tone thresholds of 40dB or better in at least one ear at 1000, 2000, and 4000Hz (Ventry & Weinstein, 1983). The control participants reported a negative history of neurological impairments, speech and/or language disorders, and medications affecting speech. The patients with PD reported being optimally medicated during the recording session. Speech intelligibility was determined in two ways: (1) using the Sentence Intelligibility Test (SIT) (Yorkston, Beukelman, Hakel, & Dorsey, 2007); and (2) using a measure of scaled intelligibility obtained by direct magnitude estimation (DME) with a modulus (Weismer & Laures, 2002; Yunusova, Weismer, Kent, & Rusche, 2005). Both procedures are described below. Speakers with PD represented a wide range of speech intelligibility, ranging from 61.0% to 99.1% on the SIT and an average of 52.1 to 339.4 on the DME task. Ten speakers with PD performed more than 1.5 SD below the control mean on the DME task.

Speaking Tasks

Participants read three sentences: *‘Sally sells seven spices,’ ‘Take the tasty tea on the terrace,’* and *‘Clever Kim called the cat clinic.’* The sentences were loaded with consonants targeting the front (‘s’, ‘t’) and back (‘k’) of the tongue, while a combination of high and low vowels was included to elicit large articulatory movements. Each sentence was repeated four times, and the order of sentences was randomized across participants. The sentences were first read at a normal comfortable speaking rate and loudness, followed by loud, clear, or slow speaking conditions presented in a random order. Speaking condition instructions were adapted from previous studies (Perkell, Zandipour, Matthies, & Lane, 2002; Tjaden, Sussman, & Wilding, 2014; Tjaden & Wilding, 2005). For example, 'please speak twice as loud as your normal voice' was used to elicit loud speech. In addition to the instruction to speak 'twice as slow' for the slow rate condition, participants were asked to prolong their speech sounds, instead of inserting pauses between the words. For the clear condition, participants were asked to read in a 'clear style of speech, as if making yourself understood in a noisy environment.' Sentences produced with errors, or not following the instructions, were not accepted and were re-recorded. The stimulus materials and their manner of presentation were pilot-tested to ensure usability and accessibility for the participants (Hamidi, Baljko, Economopoulos, Livingston, & Spalteholz, 2015). The total number of sentences recorded was 1968 (3 sentences x 4 repetitions x 4 conditions x 41 speakers).

Instrumentation and Signal Processing

Articulatory movements were captured using a 3D electromagnetic tracking system, the Wave Speech Research System (WAVE; Northern Digital Inc., Canada), which records articulatory positions of small sensors attached to the articulators with sub-millimeter accuracy when in close proximity to the field generator (Berry, 2011). Kinematic data were recorded at a maximum allowed sampling rate of 400Hz. Simultaneously, a synchronized acoustic signal was recorded directly onto the hard drive of a computer at 22 kHz, and 16 bit resolution, using a lapel microphone (Countryman B3P4FF05B) positioned approximately 15cm from the speaker's mouth.

One six degree-of-freedom (DOF) reference sensor attached to a headband was placed on the forehead during recording. Two five-DOF sensors were attached to the mandibular gum line, between the canine and incisor teeth on both sides of the jaw using stoma adhesive (Stomahesive, Convatec). Two other five-DOF sensors were placed on the midline of the tongue using PeriAcryl®90 Oral Tissue Adhesive, non-toxic dental glue (Glustitch). One sensor was placed at the tongue blade (TB), and a second sensor was placed at the tongue dorsum (TD), 10mm (mean = 10.45mm, *SD* = 1.32mm) and 30mm (mean = 28.47mm, *SD* = 2.86mm) from the tongue tip, respectively. Jaw and tongue sensor positions were collected relative to the head, following the built-in WAVE positional-transformation routine. Tongue movements were not decoupled from the jaw movements.

Occasionally during data collection sensors became loose on the tongue and were removed, or their position was not trackable due to a suboptimal head position within the electromagnetic field, leading to missing data and/or distinct artifacts in the data. As a result, tongue blade data were not analyzed for one control speaker, and tongue dorsum data were omitted for seven speakers (PD, $n = 2$; control, $n = 5$).

The kinematic data were post-processed using MatLab 2014a software (MathWorks, 2014). The post-processing steps included: (1) interpolating and resampling the data uniformly at 400Hz; and (2) low pass filtering the data using a 5th-order Butterworth filter at 15Hz to remove high-frequency noise. The acoustic recordings were post-processed using Goldwave Version 6 software (Goldwave Inc., 2015) to remove non-speech high-frequency noise, attributed to the WAVE, from the signal using a high-pass filter at 9.8kHz.

Intelligibility Ratings and Procedures

Speech intelligibility was determined using the SIT (Yorkston, Beukelman, et al., 2007) to allow comparison to patient demographics in other studies, and using the DME with modulus approach to obtain scaled intelligibility scores for use in statistical analysis.

Sentence Intelligibility Test. During the SIT, participants with PD were asked to read a list of 10 sentences varying in length from 5 to 15 words that were randomly generated by the test software. The recordings were transcribed by one naïve listener who was unfamiliar with the test materials and the speech patterns of the participants. The listener heard the stimuli through external noise-cancelling headphones (BOSE QuietComfort 15) in a quiet room and could listen to the recordings up to a maximum of two times. SIT scores were calculated by the software as the percent of words correctly transcribed out of the total number of words.

Direct Magnitude Estimation Task. For the DME task, the three experimental sentences recorded in the normal speaking condition by all speakers were rated by a group of naïve listeners. Prior to rating, the recordings were equated for root-mean-square amplitude to minimize intelligibility effects due to audibility (Tjaden et al., 2014), and the stimuli were then mixed with speech-shaped noise at a signal-to-noise-ratio (SNR) of -5dB (Van Engen, Phelps, Smiljanic, & Chandrasekaran, 2014); both processing steps were completed using Goldwave Version 6 software (Goldwave Inc., 2015).

Forty listeners were recruited (M/F = 9/31, mean age = 24.68±4.14), and all had pure tone thresholds of 20dB or better for frequencies ranging from 250 to 8000Hz bilaterally. The listeners were native speakers of English, had at least a high school diploma, and reported no history of speech or language disorders. The recordings were presented once through headphones (BOSE QuietComfort 15) in a sound-treated booth (Industrial Acoustics Company, Inc.) using Eprime Software 2.0 (Psychology Software Tools, Inc.). The listeners scaled intelligibility of each sentence based on ‘the ease with which the sentence was understood” with reference to a modulus, which was assigned a score of 100 and repeated every 10 sentences. The stimuli (all repetitions of the experimental sentences in the normal speaking condition, $N = 492$) were divided into eight subsets; each subset contained recordings from five to six speakers ($n = 60$ and $n = 72$, respectively), with at least two speakers from each group (PD, controls). The subsets were each judged by five randomly assigned listeners.

Intra-rater reliability was calculated based on 10% of repeated stimuli in each subset, and a minimum coefficient of $r = .60$ was required to include a listener’s data in the analysis. Thirty-seven of the 40 listeners achieved this criterion. Pearson product-moment correlations across the remaining 37 listeners ranged from .60 to .90 (mean = .75, *SD* = .08), representing a moderate-strong agreement within listeners. To examine interjudge reliability, an intraclass correlation coefficient (ICC) was calculated for all subsets of listener data (Neel, 2009; Tjaden et al., 2014) and the average ICC values ranged from .53-.86 (mean = .76, *SD* = .12). All intra- and interjudge correlations were statistically significant ($p<.001$). The geometric mean of ratings across listeners in a subset was used to calculate the scaled intelligibility score for each recording, and then averaged across the three sentences for each speaker.

Measurements

Sentence onsets and offsets were determined using acoustic landmarks in a combined waveform and wideband spectrographic display (TF32) (Milenkovic, 2005). Sentence duration, in milliseconds (ms), was measured from the acoustic onset and offset for each sentence. Acoustic boundaries were chosen because of the differences in the kinematic landmarks between sentences. The acoustic landmarks were also used for parsing kinematic data into individual sentences.

Sound Pressure Level (SPL) and articulatory rate were calculated for each sentence to assess whether speakers adjusted speaking rate and loudness following verbal instructions. Mean SPL was calculated for each recording and expressed relative to the normal condition. The mean root-mean-square amplitude was determined for vowel intensities using a MatLab function *rms*, and voltages were converted to decibels (dB SPL) with reference to each speaker's recordings in the normal condition (Darling & Huber, 2011; Tjaden et al., 2014). Articulatory rate was measured as the number of syllables per second (SPS) for each sentence. As the sentences were relatively short and did not contain pauses greater than 200ms, pause durations did not have to be removed prior to the calculation of articulatory rate.

Kinematic measures were chosen based on prior studies of dysarthria in PD demonstrating changes in size and speed of speech movements (e.g. Walsh & Smith, 2012), and were calculated for the jaw, tongue blade, and dorsum. Example measurements for a single sentence ('Sally sells seven spices') produced by a control speaker (C28) in the normal speaking style are shown in Figure 1. The measures are shown in two dimensions for simplification; however, the measurements were conducted in three-dimensional space.

(1) Articulatory working space (AWS) was used to capture the overall movement size of an articulator during each sentence (Bunton & Leddy, 2011; Weismer, Yunusova, & Bunton, 2012). AWS was calculated as the volume of a convex hull encompassing the movement trajectory of the sentence (mm^3), using a MatLab function *convhull*.

(2) Movement range along the first principal component (PC1 range; mm) was measured to examine the movement size along the dimension accounting for greatest variance (Adams,

Weismer, & Kent, 1993; Mefferd & Green, 2010; Yunusova et al., 2010). Principal component analysis was conducted for each sentence trajectory; the principal components were identified and the trajectory data were re-expressed in the coordinate system defined by the principal components. In Matlab, the range of movement along the first principal component axis was measured as the distance between extrema in the new axes defined by the principal components using the *princomp* function.

(3) Average speed (mm/s) during each sentence was computed in order to represent the overall tendency across a sentence, instead of peak values associated with specific sounds or gestures. In Matlab, average speed was calculated for each articulator as the mean absolute value of the first derivative of 3D Euclidean distance from the onset to the offset of the sentence (Yunusova et al., 2010).

Statistical Analysis

Data were first visually examined for outliers and variable distributions. Outliers, defined as data points greater than 3 SD above the group mean for each articulator and condition were removed; 166 (1.78%) data points (based on individual sentence repetitions) were removed for the control group, and 58 (0.74%) for the PD group. Outliers were randomly distributed across articulators and conditions. All analyses were conducted in R version 3.2.3 (R Core Team, 2015). The packages lme4 (v1.1-10) (Bates, Maechler, Bolker, & Walker, 2015) and lmerTest (v.2.0-30) (Kuznetsova, Brockhoff, & Christensen, 2016) were used for linear mixed-effect (LME) models. Denominator degrees of freedom were calculated based on the Satterthwaite approximation to account for differing variances. An alpha level of .05 was used for all main effects.

The effect of instruction (i.e., responding to cues for loud, clear, and slow speech) was evaluated by measuring dB SPL and percent change in articulatory rate, both relative to the normal condition, and employing two-way analyses of variance (ANOVAs) with the main effects of condition and group and a condition-by-group interaction. Post-hoc pairwise comparisons were conducted using t-tests with Bonferroni-correction for multiple tests to control for family-wise error rate.

LME models were used for all remaining analyses to account for inter-subject variability and multiple repetitions per speaker. Separate models were run for each articulator (jaw, TB, TD) and measure (AWS, PC1 range, average speed, sentence duration). Standard diagnostic plots suggested non-constant error variance in these models and the data were log-transformed for the analyses. Interaction terms were included in the final model when inclusion of the interaction term led to a better model fit, as determined by smaller absolute Akaike Information Criterion (AIC) values.

First, to evaluate the effect of PD on sentence-level speech kinematics, group differences (PD versus controls) were examined for the normal speaking condition. In the LME models, group and sentence were specified as fixed factors and subject was included as a random intercept. Sentence was included as a fixed factor due to inherent differences in movement sizes and durations between sentences. To assess if specific sentences were more sensitive to group differences, the interaction between group and sentence was examined. Paired comparisons were conducted by fitting additional LME models, and p-values were Bonferroni-corrected.

Further, the effect of speech intelligibility on articulatory kinematics was assessed in the normal speaking condition for the speakers with PD. LME models predicted articulatory kinematics from scaled (DME) intelligibility scores. Separate models were specified per sentence, and subject was included as a random intercept.

Finally, the effect of speaking condition (normal, loud, clear, and slow) on articulatory kinematics was evaluated using LME models, where speaking condition and group were specified as fixed factors, sentence was added as a covariate, and the intercept term was allowed to vary by subject. To examine if both groups responded in a similar way to varying speaking conditions, the two-way interaction between condition and group was evaluated. Post-hoc comparisons were performed by fitting additional LME models for significant effects and were adjusted using Bonferroni correction.

Results

Effect of Instruction on Measures of Loudness and Articulatory Rate

Figure 2 shows changes in dB SPL and articulatory rate in loud, clear, and slow conditions, relative to the normal condition. Larger change values correspond to louder dB SPL and slower articulatory rate, respectively. Analysis of change in dB SPL revealed a significant effect of condition ($F(2, 116) = 28.34$, $p < .001$), but not group ($F(1, 116) = .36$, $p = .552$). The condition-by-group interaction was not significant ($F(2, 116) = 1.03$, $p = .359$). Pairwise comparison between conditions showed that the magnitude of increase in SPL was greater for loud as compared to clear ($p < .001$) and slow conditions ($p < .001$). dB SPL results between clear and slow conditions were not significantly different.

Change in articulatory rate differed significantly between groups ($F(1, 115) = 8.19$, $p = .005$), as well as conditions ($F(2, 115) = 36.22$, $p < .001$) but there was no interaction between condition and group ($F(2, 116) = 1.30$, $p = .276$). Articulatory rate was slower in loud, clear and slow conditions, as compared to the normal condition. Across conditions, speakers with PD slowed their articulatory rate to a lesser extent than control speakers. For both groups, articulatory rate decreased to the greatest extent in slow as compared to both loud ($p < .001$) and clear ($p < .001$) conditions. Greater slowing of articulatory rate was observed in clear relative to the loud condition ($p < .001$).

Group Differences in the Normal Speaking Condition

Table 2 summarizes the data by measure, articulator, condition, and group. For all of the group analyses, inclusion of the group-by-sentence interaction term did not result in a better model fit and the interaction term was not included in the final models. A significant group difference was detected for AWS of the jaw ($F(1, 39.14)= 7.17$, $p = .011$); smaller movements of the jaw were observed for speakers with PD as compared to controls. Analysis of sentence durations also revealed a significant group effect ($F(1, 39.28) =4.16$, $p = .048$), with speakers with PD showing shorter sentence durations than the control group. PC1 range (Jaw, ($F(1, 39.26)= 0.67$, $p = .419$); TB, $F(1, 38.06) =0.51$, $p = .478$); TD, $F(1, 27.53) =.31$, $p = .584$) and average speeds (Jaw, $F(1, 39.08) =1.80$, $p = .187$; TB, $F(1, 37.07) =3.62$, $p = .065$; TD, $F(1, 28.81) =2.56$, $p = .120$) for all articulators were not significantly different between groups. Further, no differences were detected between groups for AWS of the tongue blade ($F(1, 37.62) =0.06$, $p = .810$) or tongue dorsum ($F(1, 27.60) =0.01$, $p = .975$).

Kinematic measures showed substantial variability among speakers in the PD group, who differed greatly in the severity of their intelligibility impairment. Using scaled intelligibility as a predictor of articulatory kinematics, a positive association was found between scaled intelligibility and kinematic measures of the jaw, tongue blade, and tongue dorsum. Across all sentences, a positive association was found between PC1 range of the tongue blade and intelligibility (s, $F(1, 16.98) = 10.56$, $p = .005$; t, $F(1, 17.80) = 8.87$, $p = .008$; k, $F(1, 17.97) =$

6.55, *p* = .020). For the tongue dorsum, AWS of the ‘t’ sentence was positively associated with intelligibility (*F*(1, 14.54) = 5.67, *p* = .031). Further, positive associations between tongue dorsum PC1 range and intelligibility of the ‘s’ and ‘t’ sentences neared significance (s, *F*(1, 12.90) = 4.65, *p* = .051; t, *F*(1, 14.59) = 4.55, *p* = .050). For the jaw, PC1 range of the ‘k’ sentence was positively associated with intelligibility (*F*(1, 17.89) = 5.78, *p* = .027). For these significant associations, higher ratings of scaled intelligibility were associated with larger articulatory movement size. Scaled intelligibility was not associated with the measures of average speed or sentence durations.

Articulatory Kinematics across Speaking Conditions

Figure 3 shows means and standard errors for all kinematic measures across speaking conditions. Table 3 reports findings for significant pairwise comparisons for the main effect of condition when controlling for group and sentence.

Jaw. Analysis of jaw AWS revealed a significant difference by group (*F*(1, 39) = 9.59, *p* = .004) and condition (*F*(3, 1774.40) = 117.98, *p* < .001). The interaction between condition and group was also significant (*F*(3, 1774.40) = 8.60, *p* < .001). Across conditions, smaller jaw AWS was observed for speakers with PD than controls. Further analysis revealed that both groups increased their AWS in loud, clear, and slow speaking conditions, compared to the normal condition. For the speakers with PD however, loud, clear, and slow jaw AWS differed significantly (loud > clear > slow > normal). For controls, the increase in jaw movement size was similar across conditions (loud = clear = slow).

PC1 range of the jaw differed across conditions as well, as indicated by a significant main effect of condition (*F*(3, 1771.35) = 113.80, *p* < .001). The main group effect (*F*(1, 39.07) = 2.18, *p* = .148) was not significant, and the condition-by-group interaction term was not included in the final model. Post hoc analysis revealed that all contrasts between conditions were significant, with the largest PC1 range observed during loud, followed by clear, slow, and normal conditions for both groups (loud > clear > slow > normal).

A significant effect of condition was found for average speed of jaw movements (*F*(3, 1770.10) = 382.12, $p < .001$), without a group effect (*F*(1, 39.00) = 2.09, $p = .157$). The condition-by-group interaction was not assessed in the final model. For both groups, faster average speeds were observed in the loud condition as compared to all other conditions; and slower average speeds were observed in the slow condition as compared to all other conditions.

Tongue blade. Statistical analysis of TB AWS showed a significant main effect of condition (*F*(3, 1676.70) = 78.73, $p < .001$) and a significant interaction between condition and group (*F*(3, 1676.70) = 6.86, $p < .001$). The main effect of group was not significant (*F*(1, 38.70) = 0.47, $p = .495$). Post-hoc analysis by group revealed that the pattern of change in AWS across conditions was the same for both healthy controls and speakers with PD. For both groups, AWS was statistically larger in loud, clear, and slow speaking conditions, compared to the normal speaking condition. Further, AWS was similar between loud, clear, and slow conditions. Although the pattern of change was the same for both groups, there was a difference in magnitude of change between the two groups with control speakers increasing their AWS to a greater extent as compared to speakers with PD (Figure 3).

There was a significant effect of condition on PC1 range of the TB (*F*(3, 1726.68) = 68.21, $p < .001$), without a main effect of group (*F*(1, 38.23) = 0.15, $p = .702$). The final model did not include the condition-by-group interaction term. Pairwise comparisons revealed that speakers in both groups increased their PC1 range in loud, clear, and slow conditions, relative to the normal condition, and loud PC1 range was greater than the slow condition.

Examination of average speeds indicated a significant main effect of condition (*F*(3, 1725.22) = 400.99, *p* < .001), but not a main effect of group (*F*(1, 37.92) = 2.90, *p*= .097). The condition-by-group interaction term was not included in the final model. All contrasts between conditions were significant. For both groups, loud condition elicited the fastest speeds, followed by normal, clear, and slow conditions.

Tongue dorsum. TD AWS varied significantly across conditions (*F*(3, 1250.10) = 48.04, *p* < .001) without a main effect of group (*F*(1, 28.74) = 0.21, *p* =.650). The condition-by-group interaction was not assessed in the final model. Post-hoc pairwise comparisons showed that TD AWS was statistically larger in loud, clear, and slow speaking conditions, compared to the normal speaking condition for both groups. The increase in TD AWS was similar across conditions (loud = clear = slow).

Analysis of PC1 range showed a significant main effect of condition (*F*(3, 1264.14) = 46.39, *p* < .001) and again, similar results for both groups (group effect, *F*(1, 28.65) = 0.30, *p* < .587. The condition-by-group interaction term was not included in the final model. Post-hoc analysis revealed that PC1 range increased during loud, clear, and slow conditions, as compared to the normal speaking condition. Further, PC1 range was similar between loud, clear, and slow conditions.

There was a significant main effect of condition for TD average speed (F(3, 1275.00) = 269.79, p < .001), but not a main effect of group (*F*(1, 28.93) = 3.52, *p* = .071). The final model did not assess the condition-by-group interaction. Pairwise comparisons showed that all conditions differed from normal in average speed; fastest speeds were observed in the loud condition, followed by normal, clear, and slow conditions for both groups.

Discussion

Summary of Findings

The current study examined the effect of speech intelligibility and varying speaking conditions on sentence-level articulatory kinematics in speakers with PD and control speakers. We found that speakers with PD had smaller than normal jaw movements as well as shorter sentence durations, as compared to control speakers. The measures of the tongue and, to a lesser degree, jaw movement size varied with speech intelligibility, with more affected participants showing greater movement reduction. There was also evidence for certain sentences to be more sensitive to variation in speech intelligibility (e.g., ‘k’ versus ‘t’ or ‘s’ sentences for the jaw). Speaking conditions elicited distinct patterns of movements that were generally similar in direction between PD and control groups across all articulators. Movement size increased for all conditions relative to normal speech; faster average speeds were elicited during loud but not clear speech, and slower than normal average speeds were elicited during slow speech across the jaw, tongue blade, and tongue dorsum. Differences in movement size of the jaw and tongue blade between loud, clear, and slow conditions, however, varied between controls and speakers with PD.

Articulatory Impairment in PD: Evidence of Hypokinesia and Timing Disturbance

Existing literature commonly reports evidence of jaw/lip movement reduction (hypokinesia) in PD at the segmental level, (e.g. Forest et al., 1989; Walsh & Smith, 2012), while a single study observed this effect at the sentence level (Walsh & Smith, 2012). Our findings extended the sentence-level analysis to encompass movements of the tongue blade and dorsum. Our results, while agreeing with Walsh and Smith (2012) regarding movement reduction in the jaw, did not show changes in the tongue blade or tongue dorsum at the sentence level, indicating a pattern of differential impairment.

An early observational study of dysarthria in PD suggested a progression of impairment, from laryngeal symptoms early in the disease course to involvement of the tongue dorsum, tongue blade, and finally the lips (Logemann et al., 1978). Differential impairment of articulators in PD was later reported for the jaw and lips as well as for the jaw and tongue (Connor et al., 1989; Forrest et al., 1989; Yunusova et al., 2008). A greater magnitude of impairment for the jaw than the lower lip (Connor et al., 1989; Forrest et al., 1989) and for the tongue dorsum relative to the jaw and tongue blade (Yunusova et al., 2008) have been reported. In contrast to the vowel kinematic analysis of Yunusova et al. (2008), our present findings revealed a more prominent jaw than tongue impairment at the sentence level.

The pattern of differential impairment might be explained by physiological differences in the jaw and tongue musculature. Forrest et al proposed that the proprioceptive deficit leading to difficulties sensing jaw position in PD (Schneider, Diamond, & Markham, 1986) may be compensated for by holding the jaw in a fixed position during speech (Forrest et al., 1989), when the tongue, particularly the tongue blade, may be free to move more extensively. Post hoc, we explored the relationship between the jaw and tongue by statistically controlling for the contribution of the jaw to tongue movement (Shellikeri et al., 2016). The data revealed that when controlling for jaw movement, significantly faster movements of the tongue blade were observed for speakers with PD as compared to controls, suggesting a possible compensatory function of the tongue blade in response to the jaw deficit ($F(1, 32.17) = 4.80$, $p = .036$). No differences between groups were detected for the tongue dorsum when accounting for movements of the jaw. In order to more carefully assess the independent movement of articulators and examine patterns of compensation, tongue movements need to be decoupled from the jaw (Henriques & Van Lieshout, 2013; Westbury, Lindstrom, & McClean, 2002). Testing of a jaw-correction algorithm applicable to the NDI WAVE data, based on translational and rotational information, is currently in progress. Additionally, examination of the differential impairment longitudinally would be helpful in shedding light on the progression of PD across different articulators and muscle groups.

Interestingly, our data did not show group differences in average movement speed for any of the articulators. This finding contradicts previous reports of bradykinesia reported for jaw and tongue movements at the segmental and sentence levels (Ackermann et al., 1997; Forrest & Weismer, 1995; Forrest et al., 1989; Weismer et al., 2012). Only one study to date reported the reduction of jaw velocity in PD at the sentence level using a measure that included 80% of points in the velocity trajectory of an entire sentence (Walsh & Smith, 2012). In contrast to our study, the sentences in Walsh and Smith’s study primarily contained bilabial consonants and required large movements of the jaw (e.g. “The boys and the pipers baked moist pumpkin pies”), and did not show differences in sentence durations between speakers with PD and controls. Our sentences had a more diverse phonetic composition, which may have led to the present results. Additionally, a reduction in movement size observed in our study coincided with shorter sentence durations, allowing for average speeds to be maintained. Notably, while articulatory movements may not have become slower on average during sentence production, subtle changes in the control of speed may have occurred throughout the movement trajectories associated with specific sounds (opening/closing gestures) that may not have been detected with our measure. Further studies examining articulatory movement speed across a range of speech tasks are needed to understand if and how bradykinesia manifests in speech articulators in PD.

The Effect of Speech Intelligibility on Articulatory Movements

The results of the current study pointed to a positive association between movement size of the jaw, tongue blade, and tongue dorsum and scaled intelligibility. Across articulators, smaller movements were associated with lower ratings of intelligibility. These findings are generally consistent with previous literature suggesting that more severely affected speakers produce smaller jaw movements at the segmental level (Forrest et al., 1989). A similar association, however, was not observed between movement speed and speech intelligibility, which has previously been reported for passage level data (Weismer et al., 2012).

The relationship between declining speech intelligibility and objective (acoustic or kinematic) measures of articulatory performance has been at the center of the dysarthria literature because it underlies the link between the movement disorder in PD and its relevance to speech communication. By establishing measures that are sensitive to variation in intelligibility, we can then use them to assess the degree of neuro-motor disease severity as well as set targets for treatment, with the overall goal of improving speech intelligibility. The finding of a significant association between articulatory movement size and perceived speech intelligibility impairment observed in this study highlights the important contribution of speech movement to communication in PD. This finding was most consistent across all sentences for the tongue, despite the most pronounced group differences associated with changes in the jaw. A reasonable target for treatment may, therefore, be to focus on the enlargement of tongue movement size, and may be addressed by using stimuli that specifically require relatively large movements size (see Yunusova et al., 2017).

Effect of Stimulus Materials

At the sentence level, our findings suggest that certain sentences might be more sensitive to disease-related changes in PD. This idea has been discussed in the past in both kinematic and acoustic literature (Yunjung Kim et al., 2009; Rosen, Goozée, & Murdoch, 2008; Yunusova et al., 2008) in the context of developing a set of sensitive assessment materials as well as establishing efficient and effective therapy techniques for various dysarthria types. In this study, the sentence requiring the largest size of jaw movement ('k' sentence) and those requiring smaller, finer control of tongue ('s' and 't' sentences) were more sensitive to variation in speech intelligibility. These findings are important to consider in the selection of stimuli for assessment and treatment of hypokinetic dysarthria. The sentences in the current study, however, were not controlled for linguistic or motoric complexity, which might be important to consider in future studies.

Impact of Speaking Conditions on Jaw and Tongue Movements in PD

Speaking style manipulations are often used in the treatment of dysarthria with the overall goal to maximize intelligibility (Johnson & Pring, 1990; Park, Theodoros, Finch, & Cardell, 2016; Ramig, Countryman, Thompson, & Horii, 1995; Van Nuffelen, De Bodt, Vanderwegen, Van De Heyning, & Wuyts, 2010). Without knowing the underlying mechanism of how these approaches work, however, it is difficult to assess why one approach is effective for some speakers but not for others. Previous research reported systematic changes in articulatory movements under various speaking conditions (Darling & Huber, 2011; Dromey, 2000; Goozée et al., 2011; Kleinow et al., 2001). While the previous studies have typically focused on the impact of a single speaking condition on a single articulator (i.e. lip or tongue) and measures of movement size and speed at the segmental level only, our study extended the previous findings reporting on multiple articulator performances at the sentence level.

When comparing the effect of different speaking styles across the same group of people, we could see that all conditions resulted in an increase in movement size across all of the articulators relative to normal habitual speech. Our results also suggested that loud speech resulted not only in the upscaling of movement size but also in increasing average speed for the jaw, tongue blade, and tongue dorsum. While loud speech appears to address both hypokinetic and bradykinetic signs in PD, it is important to consider that higher movement speeds observed in this condition may also be associated with greater articulatory effort (Perkell et al., 2002). Much of the research relating to loud speech intervention in PD has been conducted in the context of the Lee Silverman Voice Treatment (LSVT) (Ramig et al., 1995; Ramig et al., 2001), the most common behavioural treatment for hypokinetic dysarthria that trains the loudness strategy through a highly structured treatment program. LSVT is based on the premise that increased loudness results in increased movement size and speed, although neither measure has been used as an outcome measure in LSVT clinical trials. Poorer outcomes of LSVT, however, have been noted for speakers with significant articulatory/rate disorders (Fox, Ebersbach, Ramig, & Sapir, 2012). For these speakers, a strategy that results in an increase in articulatory movement size and speed may not be sufficient to achieve improvements in speech quality. Systematically examining changes in speech intelligibility under various conditions would be the next important step in this line of research.

Clear speech, on the other hand, led to an increase in movement size across articulators while maintaining speed of the jaw and slowing tongue blade and dorsum movement. The finding of maintained/slowed articulatory speeds during clear speech is in contrast to a previous study where lip movement speeds were reported to increase in clear speech tasks (Dromey, 2000). In addition to differences in speech material, this discrepancy may be explained by a difference in speaking instructions, which can have an effect on kinematic and acoustic measures of speech (Darling & Huber, 2011; Lam & Tjaden, 2013). In the study by Dromey, the instruction focused on exaggerating movements of the mouth, in contrast to ‘making yourself understood in a noisy environment’ in our study. While clear speech has been effective as part of a broader treatment program for dysarthria in PD (Johnson & Pring, 1990), studies examining clear speech as a structured treatment approach for hypokinetic dysarthria have not yet been conducted (see, however, Park et al., 2016). An increase in movement size and slower tongue speeds observed in our data may allow for greater articulatory precision for speakers with PD when using a clear speech strategy.

Slow speech in our study was characterized by an increase in movement size as well as slower speeds across articulators, which may have enabled speakers to achieve greater distinctiveness between articulatory targets (Van Nuffelen et al., 2010). Measures of movement size and speed have not previously been reported for slow speech in PD; however, a study of lip movement showed increased variability when speaking at a slow rate of speech (Kleinow et al., 2001). Treatments targeting a slow rate of speech have been widely used in dysarthria, including patients with PD, albeit with mixed results, (Yorkston, Hakel, Beukelman, & Fager, 2007). In this study, we elicited slow rate by encouraging speakers to prolong their speech sounds without inserting pauses in the current study resulting in changes in articulation. Future studies examining the effects of different slow rate instructions on both articulation and pausing would be helpful in determining optimal rate reduction strategies for dysarthria treatment.

Even though distinct patterns of movement were found for each speaking condition relative to normal speech, speakers with PD and control speakers used different control strategies to vary movement size between loud, clear, and slow conditions, as indicated by a number of significant condition-by-group interaction effects. Differential control strategies between groups have previously been reported at the segmental level (Darling & Huber, 2011; Goozée et al., 2011), and may reflect the property of motor equivalence, i.e. different control strategies employed to achieve the same acoustic goal (see review, Perrier & Fuchs, 2015). When speaking loudly in background noise, for example, speakers with PD increased their jaw displacement to a lesser extent than their peers (Darling & Huber, 2011). Our data agreed with the previous reports and showed that the speakers with PD did not achieve the same degree of change in movement size of the jaw and tongue dorsum as neurologically normal controls. These findings are particularly interesting considering both groups varied their rate and loudness in a similar pattern across conditions. In particular, our results highlighted that speakers with PD might need additional cues or feedback to achieve articulatory movements that are comparable to control speakers in these speaking conditions.

The current study examined the effect of a one-time instruction on articulatory movements, and direct parallels cannot be made to treatment studies targeting loud, clear, or slow speech. Nevertheless, experimental studies documenting the effect of speaking conditions can shed light on the underlying physiological changes that may occur during treatment, and as such, strengthen the scientific basis for dysarthria intervention. Future pre-post treatment studies should incorporate measures of articulatory movements to determine the physiological basis for treatment approaches in PD. Further, systematically relating these changes to changes in speech intelligibility will provide a comprehensive basis for dysarthria treatment in PD.

Conclusion

Studies of the effect of PD on sentence-level articulatory movement remain limited. Studying multiple articulators across a range of dysarthria severities allowed us to contribute a unique perspective on this debilitating disease and its impact on articulation, while sentence-level analyses increased the applicability of findings to stimuli used in speech interventions. From a clinical perspective, this study highlighted the underlying physiologic effects of common therapeutic approaches for speech rehabilitation in PD. Further work is required to understand the effect of these approaches when applied during intervention and to identify speech kinematic profiles of speakers who benefit from different treatment approaches.

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Table 1.

Summary of participant demographic and clinical characteristics.

Group	***n* (M/F)**	**Age (years)**	**MoCA (/30)**	**SIT (%)**	**DME**
Control	10/10	70.74 (9.34)	27.6 (1.35)		223.85 (29.99)
PD	16/5	68.86 (3.44)	26.06 (3.17)	92.73 (8.69)	177.73 (47.32)

Note. Values in parentheses are standard deviations. MoCA = Montreal Cognitive Assessment; SIT = Sentence Intelligibility Test; DME = Direct Magnitude Estimation Scaled Intelligibility; PD = Parkinson’s disease.

Table 2.

Means and standard deviations (SD) of the kinematic measures and sentence durations by articulator, speaking condition, and group.

Articulator	**Measure**	**Normal**		**Loud**		**Clear**		**Slow**	
		Control	**PD**	**Control**	**PD**	**Control**	**PD**	**Control**	**PD**
Jaw	AWS (mm^3)	29.53	16.60	68.90	35.37	66.07	25.68	59.36	23.90
		(23.82)	(17.69)	(65.49)	(34.92)	(61.51)	(24.51)	(52.19)	(29.67)
	PC1 Range (mm)	9.95	9.41	14.07	11.97	13.16	11.07	12.14	10.66
		(4.36)	(2.98)	(5.22)	(3.97)	(4.99)	(3.71)	(4.47)	(4.16)
	Average Speed (mm/s)	25.69	28.42	32.94	35.98	25.95	29.11	22.02	23.70
		(11.70)	(8.26)	(14.68)	(10.46)	(12.44)	(8.24)	(11.61)	(6.83)
TB	AWS (mm^3)	206.81	236.43	372.80	336.57	336.97	302.67	331.67	291.12
		(148.04)	(191.79)	(292.79)	(275.72)	(245.00)	(240.23)	(265.97)	(218.17)
	PC1 Range (mm)	16.05	16.90	19.67	18.97	18.95	18.68	18.10	18.51
		(3.97)	(4.78)	(5.19)	(5.32)	(5.24)	(5.31)	(4.67)	(5.32)
	Average Speed (mm/s)	42.55	54.59	50.37	62.13	39.84	53.26	35.20	45.05
		(16.28)	(15.51)	(20.68)	(17.24)	(16.42)	(14.09)	(15.05)	(14.63)
TD	AWS (mm^3)	246.64	247.05	391.71	341.50	375.18	312.75	377.80	311.55
		(169.38)	(217.92)	(290.96)	(286.24)	(291.94)	(249.13)	(291.06)	(252.15)

PC1 Range (mm)	18.94	18.18	21.47	20.45	21.41	20.54	21.82	20.48
	(3.65)	(4.57)	(4.41)	(5.37)	(4.62)	(5.38)	(3.96)	(5.11)
Average Speed (mm/s)	43.55	51.03	51.07	57.96	39.64	50.32	35.24	41.56
	(19.82)	(16.76)	(21.04)	(17.90)	(19.79)	(15.54)	(16.72)	(14.43)
Sentence Duration (ms)	2847.31	2596.35	3038.18	2631.00	4048.73	3057.48	5006.95	4069.50
	(573.93)	(631.83)	(730.23)	(633.88)	(1081.78)	(831.13)	(1942.47)	(1745.94)

Note. PD = Parkinson’s disease; TB = Tongue Blade; TD = Tongue Dorsum; AWS = Articulatory Working Space; PC1 Range = Range along the first principal component.

Table 3.

Summary of significant pairwise comparisons for analysis of speaking conditions.

Articulator	**Measure**	**Comparison**	***B***	***P***
Jaw	AWS (mm^3)	Normal < Loud	-0.69	< .001
		Normal < Clear	-0.58	< .001
		Normal < Slow	-0.47	< .001
		Loud > Clear	0.11	.037
		Loud > Slow	0.22	< .001
		Clear > Slow	0.11	.025
	PC1 Range (mm)	Normal < Loud	-0.58	< .001
		Normal < Clear	-0.36	< .001
		Normal < Slow	-0.26	< .001
		Loud > Clear	0.22	< .001
		Loud > Slow	0.32	< .001
		Clear > Slow	0.10	.002
	Average Speed (mm/s)	Normal < Loud	-0.22	< .001
		Normal > Slow	0.19	< .001
		Loud > Clear	0.21	< .001
		Loud > Slow	0.41	< .001
		Clear > Slow	0.20	< .001
TB	AWS (mm^3)	Normal < Loud	-0.37	< .001
		Normal < Clear	-0.35	< .001
		Normal < Slow	-0.32	< .001
	PC1 Range (mm)	Normal < Loud	-0.34	< .001
		Normal < Clear	-0.24	< .001

		Normal < Slow	-0.23	< .001
		Loud > Clear	0.10	< .001
		Loud > Slow	0.11	< .001
	Average Speed (mm/s)	Normal < Loud	-0.12	< .001
		Normal > Clear	0.05	< .001
		Normal > Slow	0.23	< .001
		Loud > Clear	0.17	< .001
		Loud > Slow	0.35	< .001
		Clear > Slow	0.18	< .001
TD	AWS (mm^3)	Normal < Loud	-0.33	< .001
		Normal < Clear	-0.35	< .001
		Normal < Slow	-0.31	< .001
	PC1 Range (mm)	Normal < Loud	-0.22	< .001
		Normal < Clear	-0.21	< .001
		Normal < Slow	-0.26	< .001
	Average Speed (mm/s)	Normal < Loud	-0.10	< .001
		Normal > Clear	0.05	< .001
		Normal > Slow	0.23	< .001
		Loud > Clear	0.15	< .001
		Loud > Slow	0.33	< .001
		Clear > Slow	0.18	< .001

Note. TB = Tongue Blade; TD = Tongue Dorsum; AWS = Articulatory Working Space; PC1 Range = Range along first principal component.

Figures and Captions

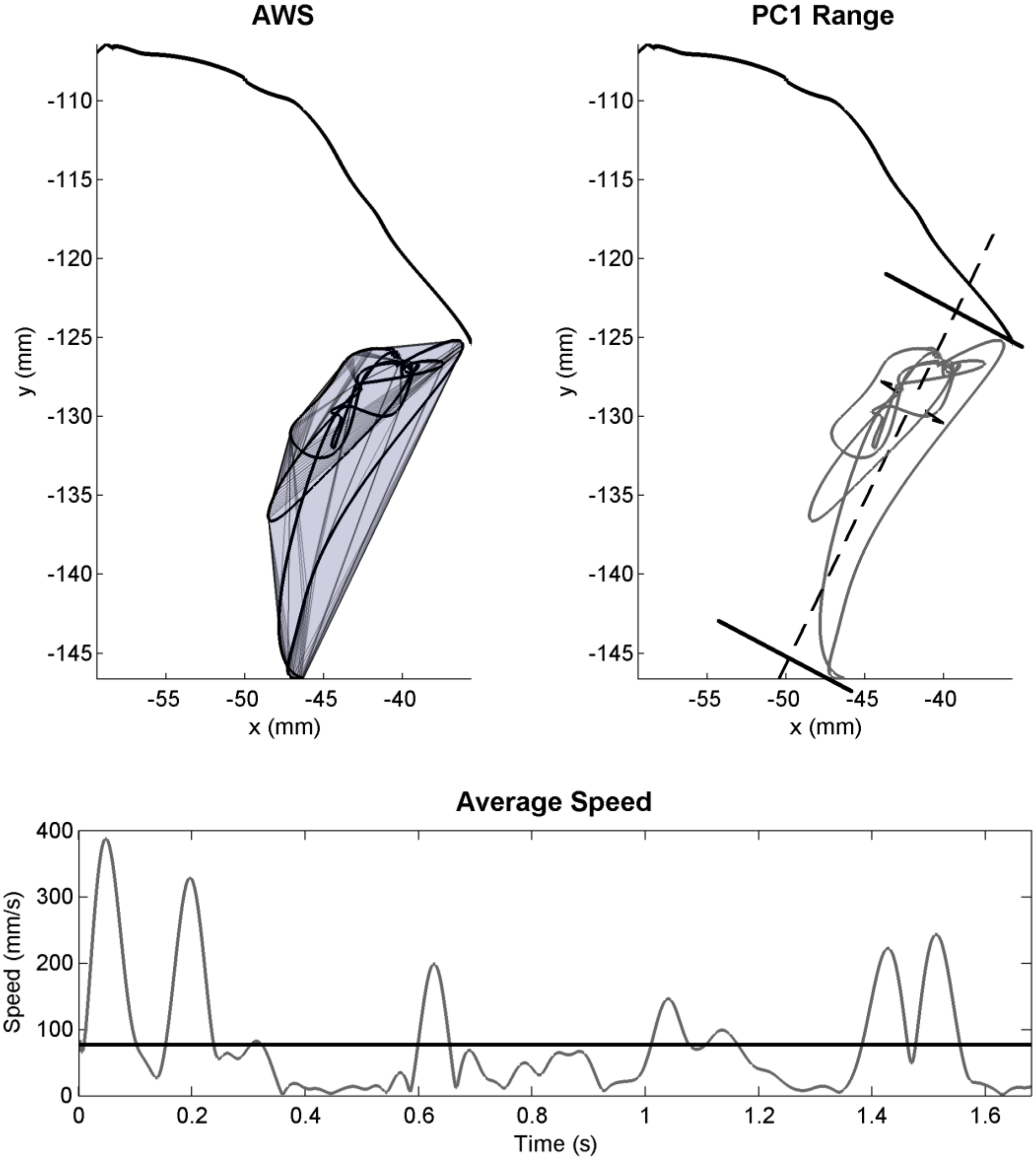

Figure 1. Articulatory working space (AWS), range along the first principal component (PC1 Range), and average speed of the tongue blade during the sentence ‘Sally sells seven spices’ for a single speaker (C28, male, aged 75 years) in the normal speaking condition.

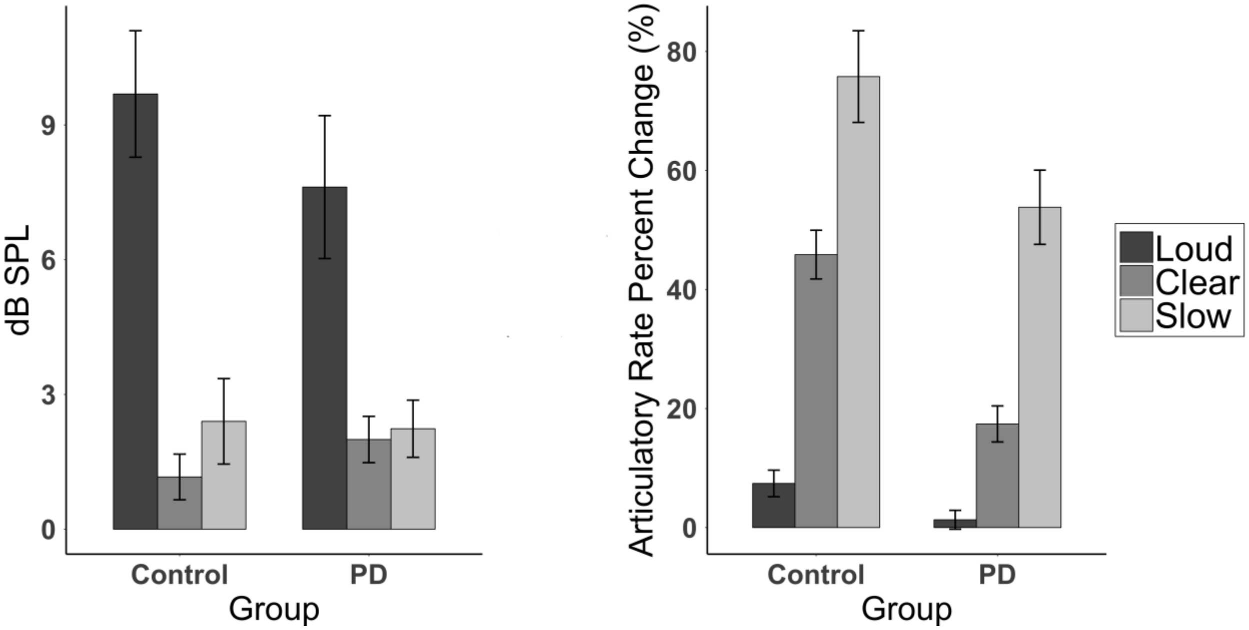

Figure 2. Mean and standard errors of change in dB SPL and articulatory rate (%) across speaking conditions relative to the normal condition.

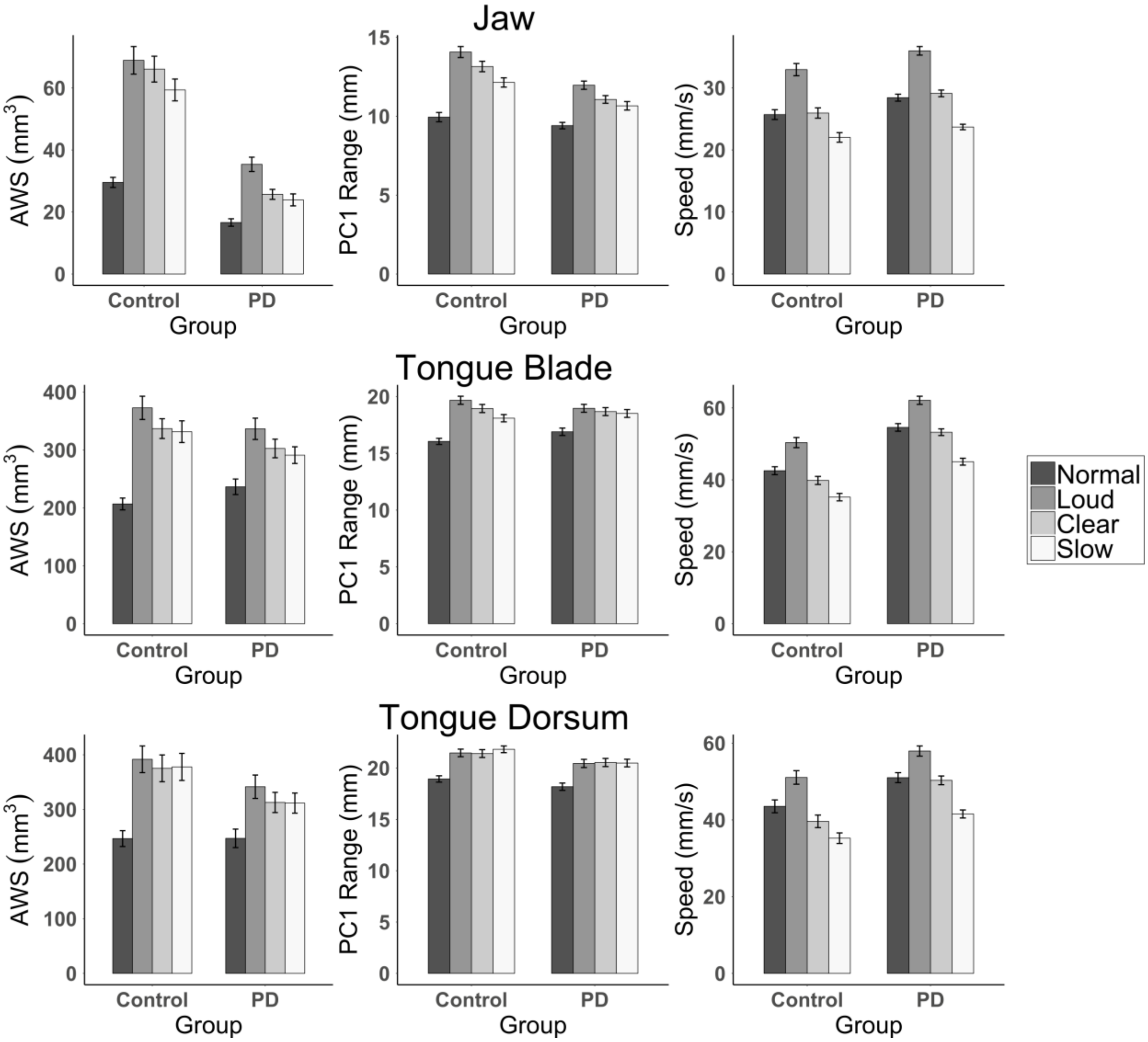

Figure 3. Mean and standard error of articulatory working space (AWS), range along the first principal component (PC1 Range), and average speed across speaking conditions.