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Vowel Acoustics in Parkinson's Disease and Multiple Sclerosis: Comparison of Clear, Loud, and Slow Speaking Conditions

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Abstract

Purpose—The impact of clear speech, increased vocal intensity, and rate reduction on acoustic characteristics of vowels was compared in speakers with Parkinson's disease (PD), speakers with multiple sclerosis (MS), and healthy controls.

Method—Speakers read sentences in habitual, clear, loud, and slow conditions. Variations in clarity, intensity, and rate were stimulated using magnitude production. Formant frequency values for peripheral and nonperipheral vowels were obtained at 20%, 50%, and 80% of vowel duration to derive static and dynamic acoustic measures. Intensity and duration measures were obtained.

Results—Rate was maximally reduced in the slow condition, and vocal intensity was maximized in the loud condition. The clear condition also yielded a reduced articulatory rate and increased intensity, although less than for the slow or loud conditions. Overall, the clear condition had the most consistent impact on vowel spectral characteristics. Spectral and temporal distinctiveness for peripheral–nonperipheral vowel pairs was largely similar across conditions.

Conclusions—Clear speech maximized peripheral and nonperipheral vowel space areas for speakers with PD and MS while also reducing rate and increasing vocal intensity. These results suggest that a speech style focused on increasing articulatory amplitude yields the most robust changes in vowel segmental articulation.

Keywords

clear speech; loud speech; dysarthria; vowels; rate reduction

Global treatment techniques for dysarthria focus on speech in a holistic, integrated manner (Hustad & Weismer, 2007). In this way, global therapy techniques extend across the time domain of an entire utterance or phrase and have the potential to simultaneously impact multiple speech components (i.e., respiration, phonation, resonance, articulation; Yorkston, Hakel, Beukelman, & Fager, 2007). Yorkston, Hakel, et al. (2007) classified rate control, increasing vocal loudness, and clear speech as global treatment techniques, and in an effort to strengthen the scientific basis for dysarthria treatment, a variety of studies have investigated the nature of the speech production adjustments associated with these therapeutic techniques. Thus, the impact of rate reduction, increased loudness, and clear speech on respiratory–phonatory behavior in dysarthria has been studied, although far more

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is known in this regard about increased loudness (Goberman & Elmer, 2005; Tjaden & Wilding, 2011; Yorkston, Hakel, et al., 2007). The impact of rate reduction and increased vocal intensity on resonance in dysarthria also has been studied (McHenry, 1997; McHenry & Liss, 2006; Yorkston & Beukelman, 1981), and clear speech holds promise as a therapy technique for mild hypernasality in dysarthria (Yorkston et al., 2001). Although knowledge of how global therapy techniques affect respiratory–phonatory behavior and resonance in dysarthria is important, of primary interest to the current study is how rate reduction, increased vocal intensity, and clear speech impact articulatory behavior in dysarthria, as inferred from the acoustic signal.

Articulatory Impairment in Dysarthria

Impaired articulation is a hallmark of dysarthria, as suggested by the inclusion of perceptual labels, such as distorted vowels, articulatory imprecision, irregular articulatory breakdown, and imprecise consonants, for all of the neurological diagnoses studied by Darley, Aronson, and Brown (1969). Kinematic, acoustic, and electropalatography studies provide potential clues about the source of these perceptual deviancies. For example, articulatory movements in dysarthria tend to have reduced displacements as well as reduced speeds and velocities, although the extent to which these movement abnormalities are revealed may depend on the articulator, phonetic context, and severity of impairment (see Darling & Huber, 2011; Weismer, Yunusova, & Bunton, 2012; Wong, Murdoch, & Whelan, 2010; Yunusova, Weismer, Westbury, & Lindstrom, 2008). Compared with healthy talkers, articulatory movements in talkers with dysarthria also are less distinct and occur in a more central position of the vocal tract (Kent & Netsell, 1978; Kent, Netsell, & Bauer, 1975). Acoustic studies provide additional support for reduced articulatory displacements and movement speeds in dysarthria as well as for the suggestion that articulatory movements are less distinctive and more centralized (e.g., Skodda, Visser, & Schlegel, 2010; Tjaden & Turner, 1997; Tjaden & Wilding, 2004; Weismer, Jeng, Laures, Kent, & Kent, 2001; Yunusova et al., 2012). These articulatory–acoustic characteristics are not unique to a particular neurological diagnosis or dysarthria and thus appear to be a general characteristic of impaired speech motor execution (Weismer & Kim, 2010).

It also has been suggested that articulatory behavior in dysarthria is uncoordinated (Darley et al., 1969). The construct of coordination has been interpreted and measured in any number of ways in the speech literature. Regardless of how coordination is defined, however, objective evidence of impaired articulatory coordination in dysarthria is limited (see reviews in Tjaden, 2007; Yunusova et al., 2008). Thus, although it has been hypothesized that a reduced rate or increased vocal intensity might enhance coordination in dysarthria, and some studies have been interpreted to suggest that coordination in the articulatory mechanism is improved when speakers with dysarthria are stimulated to use an increased vocal intensity (Dromey, 2000; Kleinow, Smith, & Ramig, 2001) or reduced articulatory rate (McHenry, 2003), it remains to be determined whether incoordination underlies impaired segmental articulation in dysarthria. Relatedly, although nonspeech studies suggest deficits in muscle strength, tone, and stability in the articulatory mechanism of dysarthria, whether these variables contribute to impaired speech sound articulation is unknown (see Tjaden, 2007; Weismer, 2006). Present evidence therefore suggests that reduced movement speeds and amplitudes as well as movements that are centralized and thus less distinctive most likely underlie impaired articulation in dysarthria.

Global Therapy Techniques and Impact on Segmental Articulation

Because impaired articulation is characteristic of virtually all dysarthrias, improving the adequacy of speech sound production is a common goal of behavioral treatments for dysarthria (Duffy, 2005). Rate reduction, increased vocal loudness, and clear speech all show potential for improving segmental articulatory behavior in dysarthria.

Rate control, in the form of a slower-than-normal speech rate, is recommended as a treatment technique for all dysarthrias (e.g., Duffy, 2005; Van Nuffelen, De Bodt, Vanderwegen, Van de Heyning, & Wuyts, 2010). Rate reduction is thought to facilitate articulatory adequacy by providing additional time for speakers to achieve more canonical vocal tract configurations or articulatory targets that are distinctive from other phonemes (Yorkston, Beukelman, Strand, & Hakel, 2010). Several dysarthria studies, most reporting speech acoustic measures, provide varying levels of support for this suggestion (Adams, 1994; Hustad & Lee, 2008; Tjaden & Wilding, 2004; Turner, Tjaden, & Weismer, 1995). For example, Hustad and Lee (2008) reported an expanded corner vowel space area when speakers with dysarthria secondary to cerebral palsy slowed their articulatory rate by using alphabet supplementation. Spectral distinctiveness of consonants may be further enhanced when a slower-than-normal rate is stimulated, at least for some speakers with dysarthria (McRae, Tjaden, & Schoonings, 2002; Tjaden & Wilding, 2004).

Increased vocal loudness for treatment of dysarthria has gained widespread popularity because of the use of the Lee Silverman Voice Treatment Loud (LSVT Loud) for hypophonia associated with Parkinson’s disease (PD) and the wealth of studies supporting its effectiveness (Sapir, Ramig, & Fox, 2011; Yorkston, Hakel, et al., 2007). Because this treatment is intended to facilitate strong, stable (i.e., non-noisy) phonation, increased vocal loudness also has been used for individuals with progressive neurological conditions, such as multiple sclerosis (MS; Sapir et al., 2001) and cerebellar dysfunction (Sapir et al., 2003). An increased vocal loudness primarily focuses on increasing movement amplitude in the respiratory–phonatory mechanism with the goal of increasing phonatory effort, vocal fold adduction, and respiratory support for speech (Yorkston, Hakel, et al., 2007). Although the respiratory–laryngeal mechanism is the focus, changes in segmental articulatory behavior have been reported. For example, Darling and Huber (2011) reported increased displacements and peak velocities for the lips and jaw when speakers with PD were stimulated to increase vocal intensity for simple laboratory sentences (see also Dromey, 2000; Goozee, Shun, & Murdoch, 2011). Acoustic studies also have reported an expanded vowel space area and/or enhanced spectral distinctiveness of consonants and vowels when speakers with dysarthria are stimulated or trained to increase vocal intensity (e.g., Sapir, Spielman, Ramig, Story, & Fox, 2007; Tjaden & Wilding, 2004; Wenke, Cornwell, & Theodoros, 2010; but see Neel, 2009; Tjaden & Wilding, 2004, for studies stimulating an increased vocal intensity in which vowel spectral distinctiveness was not enhanced). An explanation for these types of “spreading effects” remains to be determined but has been discussed in the dysarthria literature for some time (see Rosenbek & LaPointe, 1985; Sapir et al., 2011). Of note, however, the articulatory adjustments associated with an increased vocal intensity do not appear to be a by-product of a reduced rate, as articulatory changes may accompany an increased vocal intensity regardless of whether articulatory rate also is slowed (e.g., Darling & Huber, 2011; Dromey, 2000; Ramig, Countryman, Thompson, & Horii, 1995).

Finally, clear speech is a manner or style of talking characterized by exaggerated or hyperarticulation. Clear speech also is characterized by a slower-than-normal articulatory rate and increased vocal intensity relative to conversational or habitual speech, but exaggerated articulation is the focus. Clear speech also is recommended as a treatment technique for a variety of neurological diagnoses and dysarthrias, with the exception of hyperkinetic dysarthria (Duffy, 2005). Studies of neurologically typical speech suggest the feasibility of using clear speech to address articulatory impairment in dysarthria (Smiljanić & Bradlow, 2009; Tasko & Greilick, 2010), but to date, only a few published studies have investigated segmental articulatory adjustments associated with clear speech in dysarthria. Results of these studies, however, are in broad agreement with findings of neurologically typical speech. For example, Dromey (2000) reported, relative to habitual speech, increased lower lip displacements and an increase in peak velocity for hyperarticulate speech produced by speakers with PD. Goberman and Elmer (2005) also reported an increased corner or peripheral vowel space area for clear versus habitual speech produced by 7 of 12 speakers with PD.

Summary and Purpose

Rate reduction, increased vocal intensity, and clear speech all have the potential to improve segmental articulatory behavior in dysarthria, and a handful of dysarthria studies have compared a subset of these therapeutic techniques (Beukelman, Fager, Ullman, Hanson, & Logemann, 2002; Dromey, 2000; Kleinow et al., 2001; Tjaden & Wilding, 2004, 2005). Conclusions concerning the relative merits of these global therapy techniques are complicated by the varied methods and measures reported in these studies, however. Moreover, no dysarthria study has directly compared rate reduction, increased loudness, and clear speech. It is particularly interesting to compare clear speech with increased vocal intensity and rate reduction, because the suprasegmental pattern of clear speech resembles a combination of rate reduction (i.e., lengthened speech durations) and increased vocal intensity (i.e., increased SPL) and also is the only speech style that explicitly focuses on increasing movement amplitude in the articulatory mechanism (i.e., exaggerated or hyper-articulation).

The primary purpose of the current study was to compare the impact of increased vocal intensity, rate reduction, and clear speech on vowels produced by speakers with idiopathic PD and MS, as inferred from the acoustic signal. Healthy controls were studied for comparison. Rate reduction, clear speech, and increased vocal intensity are recommended therapy techniques for PD and MS, and studying multiple neurological diagnoses addresses generalizability (e.g., compare McHenry, 2003, and Kleinow et al., 2001). The present focus on vowels is consistent with other dysarthria studies as well as studies investigating clear speech in healthy talkers (e.g., Ferguson & Kewley-Port, 2007; Lam, Tjaden, & Wilding, 2012; Tjaden, Rivera, Wilding, & Turner, 2005). Moreover, although the present study focuses on vowel acoustics, acoustic cues in vocalic intervals are important for sentence intelligibility (Fogerty & Humes, 2012), and maximizing intelligibility is often a goal of dysarthria treatment. Variations in rate, loudness, and clarity were stimulated using magnitude production. As we and others have noted (e.g., Sapir et al., 2011; Tjaden & Wilding, 2004), results from studies using stimulation should not be directly compared with those using training paradigms. However, studies using experimental manipulation of speech are classified by Yorkston, Hakel, et al. (2007) as Phase I treatment research. These types of studies give an indication of the potential value of an intervention technique, and stimulation is recommended for planning intervention (Yorkston et al., 2010).

Method

Speakers

A total of 39 speakers participated, including 13 speakers with a medical diagnosis of idiopathic PD, 11 speakers with a medical diagnosis of MS, and 15 neurologically healthy controls. The PD group was composed of seven men and six women (mean age = 68 years; *SD* = 10 years), the MS group was composed of five men and six women (mean age = 55 years; *SD* = 7 years), and the control group was composed of eight men and seven women (mean age = 61 years; *SD* = 9 years). Participants with MS and PD reported no other history of neurologic disease, and control participants reported no history of neurologic disease. All speakers were native speakers of American English, had achieved at least a high school diploma, and had visual acuity or corrected acuity adequate for reading printed materials. Speakers also scored at least 26 out of 30 on the Standardized Mini-Mental State (Molloy, 1999), with the exception of one male speaker with MS who scored 25 out of 30.

Hearing aid use was an exclusionary criterion. Speakers also underwent pure-tone audiometric screening at the University at Buffalo Speech and Hearing Clinic for the purpose of providing participants with a global index of their auditory status. No one was excluded on the basis of the audiometric screening, however. Participants with MS and PD were taking a variety of symptomatic medications but had not undergone neurosurgical treatment for MS or PD. Two of the female participants with PD also reported completing LSVT more than 2 years prior to the study, and one of these individuals reported current participation in a bimonthly LSVT group refresher course. Other participants with MS and PD had received speech therapy for dysarthria in the past but were not receiving treatment at the time of the study. Control participants reported no history of speech–language disorders, with the exception of one male control who reported treatment for misarticulation of /r/ as a young child. No residual articulation impairment was evident, so this speaker was not excluded from participation.

PD and MS participants are further described in Tables 1 and 2, respectively. All speakers attended two data collection sessions scheduled approximately 1 week apart. During the first session, health history information was obtained; audiometric and cognitive screenings were performed; and a clinical speech sample, which included the Sentence Intelligibility Test (Yorkston, Beukelman, Hakel, & Dorsey, 2007) and the Grandfather Passage (Duffy, 2005), was audio-recorded. For each speaker, a 1000-Hz calibration tone also was recorded at both data collection sessions for the purpose of obtaining offline measures of vocal intensity in dB SPL from the acoustic signal (see Tjaden & Wilding, 2004). Recording procedures for the clinical speech sample were identical to those for experimental stimuli described below. Speakers with PD were recorded approximately 1 hr prior to taking anti-Parkinsonian medications.

Sentence Intelligibility Test (SIT) scores in Tables 1 and 2 reflect overall percentage correct scores for 10 student listeners. A comprehensive description of procedures for obtaining these scores for a larger group of speakers is reported in Sussman and Tjaden (2012). Briefly, listeners typed their response onto a computer and performed the task without knowledge of speaker identity or neurological status. Listeners also heard sentences at the SPL at which they were naturally produced by speakers, ranging from 68 to 83 dB SPL (Bruel and Kjaer SLM, Model 2215, C Scale) for peak amplitude of each stimulus.

Tables 1 and 2 indicate similar sentence intelligibility for the MS and PD groups (MS mean = 91%, *SD* = 3%; PD mean = 90%, SD = 3%). Average sentence intelligibility for the control group was 93% (*SD* = 2%). The mildly reduced intelligibility for the control group likely reflects the fact that sentences were randomized across speakers to maximize the difficulty of the perceptual task. Analysis of variance (ANOVA) further indicated a significant group difference in intelligibility, $F(2, 35) = 6.85$, $p = .003$. Post hoc testing, using a Bonferroni correction for multiple tests, revealed poorer intelligibility for the PD group versus controls ($p = .002$). Additional pairwise comparisons were not significant.

Although the PD group had statistically reduced sentence intelligibility relative to controls, it was our impression that both speakers with MS and with PD had a perceptible dysarthria that was not entirely captured by the SIT. Thus, to confirm and quantify this impression, we obtained scaled estimates of speech severity for the Grandfather Passage (Duffy, 2005) for all speakers. A complete description of these procedures is reported in Sussman and Tjaden (2012). Briefly, we used a computerized Visual Analog Scale (VAS) adapted from Cannito, Burch, Watts, and Rappold (1997) to obtain scaled estimates of severity from three speech-language pathologists (SLPs). Scale values in Tables 1 and 2 reflect the average judgment for the three SLPs. Task instructions were similar to those used by Weismer et al. (2001) such that SLPs were instructed to judge speech severity on the basis of voice, resonance, articulatory precision, and prosody without regard to intelligibility. Scale values closer to zero in Tables 1 and 2 indicate no impairment, and scale values closer to 1 indicate severe impairment. Average scaled speech severity for the MS group was 0.71 (*SD* = 0.16), and average scaled severity for the PD group was 0.51 (*SD* = 0.23). By comparison, average scaled severity for the control group was 0.21 (*SD* = 0.15). ANOVA indicated a significant group difference in scaled severity, $F(2, 35) = 25.33$, $p < .001$. Post hoc tests, using a Bonferroni correction for multiple tests, were significant for all possible pairwise comparisons ($p \leq .033$). Task and stimuli differences aside, the scaled estimates of severity suggest that the majority of speakers with PD and MS had a perceptible dysarthria not wholly captured by the SIT. This speech pattern, wherein intelligibility is mostly preserved but speech naturalness is reduced, is described by Yorkston et al. (2010) as mild dysarthria.

Quantitative measures of intelligibility are superior to the Darley et al. (1969) perceptual labels for classifying individuals with dysarthria and are not subject to the same biases and methodological challenges associated with impressionistic judgments of consonant imprecision, monotonous voice, and so forth (Kim, Kent, & Weismer, 2011; Weismer & Kim, 2010). However, as summarized in Sussman and Tjaden (2012), it may be of interest that we anecdotally noted that many of the speakers with PD had reduced segmental precision and a breathy, monotonous voice. Speakers with MS also had reduced segmental precision as well as prosodic and voice deficits, with some talkers perceived as having a slow speech rate coupled with excess and equal stress. Other speakers with MS presented with voice quality changes in the form of increased vocal harshness or hoarseness.

Experimental Speech Stimuli and Procedures

Speakers were audio-recorded reading 25 Harvard sentences (IEEE, 1969). Sentences were selected from the larger corpus of Harvard sentences to include at least five occurrences of each of the four peripheral vowels (/ɑ, æ, i, u/) and four nonperipheral vowels (/ɛ, ʊ, ɪ, ʌ/). Both peripheral and nonperipheral vowels were of interest as they may be differentially affected by variations in rate or clarity (Gopal, 1990; Picheny, Durlach, & Braida, 1986). Previous acoustic studies investigating how variations in rate, loudness, or clarity impact vowel production in dysarthria also have focused on peripheral vowels (e.g., Goberman & Elmer, 2005; Tjaden & Wilding, 2004), and the inclusion of nonperipheral vowels provides a more comprehensive account of vowel production characteristics and also allows for examination of peripheral and nonperipheral distinctiveness (i.e., Neel, 2008). Most vowels occurred in stressed syllables of content words. Vowels were sampled from a variety of phonetic contexts to minimize the influence of one particular type of consonant context (i.e., obstruent vowel vs. nasal vowel). Audio recording took place in a sound-treated or quiet room. The acoustic signal was transduced using an AKG C410 head-mounted microphone positioned 10 cm and 45 to 50 degrees from the left oral angle. The acoustic signal was preamplified, low-pass filtered at 9.8 kHz, and digitized directly to computer hard disk at a sampling rate of 22 kHz using TF32 (Milenkovic, 2005).

All 25 sentences were produced in habitual, clear, loud, and slow conditions. A magnitude production paradigm was used to elicit variations in clarity, loudness, and rate. Instructions for the clear condition asked participants to talk "how you might talk to someone in a noisy environment or with a person who has a hearing loss. Exaggerate the movements of your mouth. You also may be louder and slower than usual. If your regular speech corresponds to a clearness of 100, you should aim for a clearness twice as good or a clearness of 200." These instructions were modeled after those used in other published clear speech studies and were intended to maximize the likelihood that speakers would not only exaggerate articulation but would also simultaneously increase vocal intensity and reduce rate (Smiljanić & Bradlow, 2009). The subject of clear speech instruction and its potential impact on speech production characteristics was considered by Lam et al. (2012) in a study of neurologically typical speech. This topic also is considered further in the Discussion. The loud and slow conditions were elicited using the following instructions: for the loud condition, "If your regular speech corresponds to a loudness of 100, you should say the sentences twice as loud, or a loudness of 200"; and for the slow condition, "If your regular speech corresponds to a rate of 100, say the sentences at a rate half as fast, corresponding to a rate of 50." Participants were further encouraged to stretch out speech sounds, rather than inserting pauses to slow rate.

Sentences were typed on note cards, and the cards were shuffled so that a unique random ordering of sentences was obtained for each speaker and condition. All participants first read sentences in the habitual condition. Five orderings of the remaining conditions were created, and speakers were randomly assigned to an order. Participants also were allowed a brief practice period prior to recording for the clear, loud, and slow conditions to become familiar with the task. An investigator first modeled the desired speaking condition for a SIT sentence. Participants then practiced utilizing clear, loud, or slow speech for two to three different SIT sentences, with general feedback provided by the investigator.

Acoustic Analysis

Acoustic measures were obtained using TF32 (Milenkovic, 2005). The rationales for the various measures as well as measurement procedures are considered in the following paragraphs. Sentences were first segmented into *speech runs*, defined as a stretch of speech bounded by silent periods between words of at least 200 ms (Turner et al., 1995). Conventional acoustic criteria were used to identify run onsets and offsets using the combined waveform and wideband (300–400 Hz) spectrographic displays. Articulatory rate, in syllables per second, was determined for each run by counting the number of syllables produced and dividing by run duration. Articulatory rates were averaged across speech runs to yield a mean articulatory rate for each speaker and condition for use in the statistical analysis. Mean SPL of each speech run also was obtained from the root-mean-square (RMS) intensity trace of TF32 (Milenkovic, 2005). RMS voltages were exported to Microsoft Excel and converted to dB SPL with reference to each talker's calibration tone. SPL measures were averaged across runs to obtain a mean SPL for each speaker and condition for use in the statistical analysis. For one speaker with MS, technical difficulties precluded measurement of SPL for the slow or loud conditions. Measures of articulatory rate and mean SPL were obtained to determine the extent to which the slow, loud, and clear conditions elicited variations in global speech timing and intensity. Vowel durations also were obtained to evaluate the extent to which the various speaking conditions affected segmental timing. Temporal distinctiveness for peripheral–nonperipheral vowel pairs also was examined.

Vowel onsets and offsets were identified from the waveform and wideband (300–400 Hz) spectrographic displays. Vowel segment durations were computed as the time interval between the first and last glottal pulse of vowels, as indicated by energy in both the first (F1) and second (F2) formant frequencies (Tjaden et al., 2005; Turner et al., 1995). Vowel durations were averaged across the four peripheral vowels as well as the four nonperipheral vowels, yielding an average peripheral and nonperipheral vowel duration for each speaker and condition for use in the statistical analysis. In addition, duration differences for peripheral–nonperipheral vowel pairs (/i–ɪ/, /æ–ɛ/, /ɑ–ʌ/, and /u–ʊ/) were computed to examine potential change in temporal distinctiveness (i.e., Neel, 2008). For each speaker and condition, segment durations were averaged across all occurrences of each peripheral and nonperipheral vowel. For each of the four peripheral–nonperipheral vowel pairings, a duration difference was calculated for use in the statistical analysis.

Linear predictive coding–generated formant trajectories were computed for F1 and F2 across the entire duration of vowels. Formant traces generated by TF32 (Milenkovic, 2005) were visually inspected, and computer-generated errors were hand corrected. Following Hillenbrand, Getty, Clark, and Wheeler (1995), formant frequency values for F1 and F2 of each vowel were extracted from three time points, corresponding to 20%, 50%, and 80% of vowel duration. For each speaker, condition, and vowel, midpoint formant frequency values (i.e., 50% point) were averaged across tokens. These static formant frequency measures were used to calculate peripheral vowel space area and nonperipheral vowel space area. Two additional measures, referred to as Euclidean distance from habitual centroid and absolute angle difference, also were calculated from midpoint F1 and F2 averages to evaluate whether rate reduction, clear speech, and increased vocal loudness differentially affected the location of individual vowels in F1 × F2 coordinate space. Average midpoint formant frequencies for each speaker were also used to calculate spectral distance measures for the four peripheral–nonperipheral vowel pairs (/i–ɪ/, /æ–ɛ/, /ɑ–ʌ/, /u–ʊ/). Each of these measures is discussed in more detail below.

We used Heron's formula to calculate peripheral and nonperipheral vowel space areas for each speaker and condition (Goberman & Elmer, 2005; Turner et al., 1995). *Vowel space area*—or a related measure such as the Vowel Articulation Index (Roy, Nissen, Dromey, & Sapir, 2009)—is an acoustic measure thought to reflect the size of articulatory working space for vowels. Vowel space area provides an overall index of the adequacy of vowel articulation, with larger vowel space areas indicating greater articulatory position distinctiveness among vowels (Weismer et al., 2012). By itself, however, the measure does not capture the impact of rate reduction, clear speech, and increased loudness on the production of individual vowels in F1 × F2 space. Thus, vowel space area measures were supplemented with distance measures for individual vowels computed from a speaker-specific habitual centroid (see also Chung, Edwards, Weismer, Fourakis, & Hwang, 2012; Karlsson & van Doorn, 2012; Turner et al., 1995), as well as a measure reflecting angle components of these distances or vectors (for a similar approach, see Chung et al., 2012; Karlsson & van Doorn, 2012). Each of these measures is considered in the following paragraph.

For each speaker, a habitual centroid first was calculated by averaging midpoint formant frequency values for F1 and F2 across all vowels produced in the habitual condition. The formula for Euclidean distance was then used to calculate the length of the line between a speaker's habitual centroid and the corresponding average F1 × F2 coordinate for each of the eight vowels in all speaking conditions. Longer distances indicate more peripheral locations of vowels in F1 × F2 space relative to a speaker's habitual centroid. Figure 1 provides a schematic of the peripheral vowel space area, nonperipheral vowel space area, and the Euclidean distance from habitual centroid for the vowel /i/. Peripheral–nonperipheral (Euclidean) distance for /u–ʊ/ also is illustrated in Figure 1 (and discussed below). To capture potential rotational differences of vowels in F1 × F2 space in the slow, loud, and clear conditions relative to the habitual condition, a measure termed *absolute angle* *difference* also was calculated. A similar measure was reported by Chung et al. (2012) to characterize language-related differences in the location of vowels in formant space. Karlsson and van Doorn (2012) also suggested using angle components of Euclidean distance vectors to capture the direction of vowel changes in F1 and F2 space. A schematic illustrating the absolute angle difference measure is provided in Figure 2. For simplicity, angles for the vowel /ɛ/ are shown in the habitual and loud conditions. For each speaker, condition, and vowel, the angle formed by the F1 × F2 coordinate as it bisects the habitual centroid was calculated. For each of the eight vowels, an absolute angle difference was calculated for habitual–loud, habitual–clear, and habitual–slow condition pairings. For both peripheral and nonperipheral vowel categories, angle difference measures were pooled across the four vowels for statistical analysis.

Formant movement over time also is known to be important for vowel identity, and studies of neurologically typical speech suggest that clearly produced vowels have greater dynamic formant movement (e.g., Assmann & Katz, 2005; Ferguson & Kewley-Port, 2002; Hillenbrand & Nearey, 1999; Moon & Lindblom, 1994). A case study also reported increased vowel formant dynamics post-LSVT at 9 months follow-up (Sapir et al., 2003). Dynamic formant movement in the current study was quantified using lambda (λ), following Ferguson and Kewley-Port (2007). Lambda was calculated from formant values obtained at the 20% and 80% points of vowel duration, using the formula $|F1_{80\%} - F_{120\%}| + |F_{280\%} - F_{220\%}|$. Lambda measures were calculated separately for each vowel and then averaged across peripheral and nonperipheral vowel categories for each speaker and condition for the purpose of statistical analysis.

Finally, spectral distinctiveness for peripheral–nonperipheral vowel pairs (/i–ɪ/, /æ–ɛ/, /ɑ–ʌ/, /u–ʊ/) was examined. This measure is illustrated in Figure 1 for /u–ʊ/. Using average F1 × F2 coordinates, a Euclidean distance was calculated for each of the four peripheral–nonperipheral vowel pairs for each speaker and condition. Longer distances indicate relatively greater distinctiveness for a given peripheral–nonperipheral vowel pair.

Reliability

Approximately 10% of sentences were randomly selected from each speaker group and condition for the purpose of determining measurement reliability. Pearson product–moment correlations and absolute measurement errors were used to index reliability. For intrajudge reliability, the correlation between the first and second set of SPL measures was 0.99 (mean absolute difference measure = 0.21 dB, *SD* = 0.79 dB). The correlation between the first and second set of segment duration measures was 0.98 (mean absolute difference measure = 8.6 ms, *SD* = 28.3 ms), and the correlation for articulation rate measures also was 0.98 (mean absolute difference measure = 0.05 syllables/s, *SD* = 0.22 syllables/s). The correlation between the first and second set of spectral measures was 0.99 (mean absolute different measure = 0.02 kHz, *SD* = 0.05 kHz).

For interjudge reliability, the correlation between the first and second set of SPL measures was 0.99 (mean absolute difference measure = 0.20 dB, *SD* = 0.55 dB). The correlation between the first and second set of segment duration was 0.96 (mean absolute difference measure = 9.8 ms, *SD* = 19.6 ms) and for articulation rate measures was 0.99 (mean absolute difference measure = 0.05 syllables/s, *SD* = 0.17 syllables/s), respectively. The correlation between the first and second set of spectral measures was 0.99 (mean absolute different measure = 0.02 kHz, *SD* = 0.04 kHz).

Data Analysis

We carried out descriptive and parametric analyses. Using SAS Version 9.1.3, a multivariate linear model was fit to dependent variables in this repeated measures design. Each measure was fit as a function of group, condition, and a Group × Condition interaction. A variable representing gender was included in the analyses to control gender-related differences in acoustic measures. For SPL and articulation rate, the condition variable included four levels (i.e., habitual, slow, loud, clear). To reduce the complexity of the design for segment-level measures, the statistical analyses examined whether the magnitude of change differed for clear, loud, and slow conditions, relative to the habitual condition. Therefore, in addition to including gender as a covariate, the habitual condition was included as a covariate in analyses for segment-level measures. This is analogous to expressing dependent variables as difference measures (i.e., clear–habitual, slow–habitual, loud–habitual). Habitual condition data are reported in the tables and figures for completeness. A significance level of $p < .05$ was used in hypothesis testing for main effects and interactions. This was deemed appropriate for an initial study comparing how rate reduction, increased vocal loudness, and clear speech impact vowel production in dysarthria. Post hoc pairwise comparisons were made in conjunction with a Bonferroni correction for multiple tests.

Results

Sound Pressure Level and Articulatory Rate

Table 3 reports descriptive statistics for articulatory rate and SPL. Statistical analysis of articulatory rate indicated a significant group effect, $F(2, 14) = 14.18$, $p < .001$. Post hoc comparisons indicated faster articulatory rates for the PD group versus the MS ($p = .004$) and control ($p < .001$) groups. There was also a significant effect of condition, $F(3, 39) = 40.51$, $p < .001$, with reduced articulatory rates in the slow and clear conditions compared with both loud and habitual conditions ($p < .001$). Table 3 further indicates that, on average, all groups produced the slowest articulation rate in the slow condition, followed by the clear, loud, and habitual conditions. This pattern held for 10 of 15 controls, 7 of 13 PD speakers, and 7 of 11 MS speakers. The clear condition was associated with the slowest articulation rate for four control, one PD, and two MS speakers.

Statistical analysis of SPL also indicated a significant effect of group, $F(2, 14) = 19.36$, $p < .001$. Post hoc comparisons indicated that both the MS ($p < .001$) and PD ($p = .001$) groups had lower vocal intensities compared with the control group. There was also a significant effect of condition, $F(3, 39) = 64.80$, $p < .001$. With the exception of the slow–habitual contrast, post hoc comparisons indicated that all conditions were significantly different from one another ($p < .001$). Mean SPL was greatest in the loud condition for 38 of 39 speakers. In addition, the clear condition was associated with the second highest mean SPL for all speakers, with the exception of three speakers with PD.

In summary, the slow condition yielded the expected adjustments in articulation rate and no change in mean SPL relative to the habitual condition. The loud condition was associated with an increased SPL and no significant adjustments in duration relative to the habitual condition. Finally, the clear condition was associated with a reduced articulatory rate and increased vocal intensity relative to the habitual condition, with the magnitude of these adjustments being somewhat less than those for the slow or loud conditions.

Segmental Timing

Vowel durations—Means and standard deviations for vowel segment durations are reported in Table 4 as a function of group and condition. The statistical analysis for peripheral vowels (/ɑ, æ, i, u/) indicated a significant effect of group, $F(2, 14) = 8.08$, $p = .005$. Post hoc analyses indicated shorter vowels for the PD group versus controls ($p = .005$). There was also a significant effect of condition, $F(2, 26) = 16.55$, $p < .001$, with longer vowels in the slow versus the loud and clear conditions ($p < .0001$). The Group × Condition interaction also was significant, $F(4, 28) = 2.89$, $p = .04$. Post hoc comparisons indicated that only vowels for controls were significantly longer in the slow condition as compared with the clear ($p = .001$) and loud ($p < .001$) conditions. Results were identical for the nonperipheral vowels (/ɑ, ʊ, ɪ, ʌ/). Thus, details of the statistical analysis for these vowels are not reported.

As indicated in Table 4, descriptive statistics further indicated for all groups that, on average, both peripheral and nonperipheral vowel durations were longest in the slow condition, followed by the clear, loud, and habitual conditions. Inspection of individual speaker data indicated that average peripheral vowel durations for 13 of 15 control speakers, 10 of 13 PD speakers, and 7 of 11 MS speakers were longest in the slow condition. For the remaining speakers, the predominant trend was for the clear condition to be associated with the longest peripheral vowel durations. Relatedly, descriptive statistics for nonperipheral vowels indicated that 11 of 15 controls, 11 of 13 PD speakers, and 6 of 11 MS speakers produced the longest mean nonperipheral vowel duration in the slow condition. For the remaining speakers (i.e., 4 control, 2 PD, and 5 MS), nonperipheral vowels were longest in either the clear or loud condition.

Temporal distinctiveness for peripheral–nonperipheral vowel pairs—Mean duration differences for peripheral–nonperipheral vowel pairs are reported in Table 5. With a few exceptions, Table 5 suggests that duration differences tended to be maximized in the slow condition. Results of the statistical analysis for /ɑ–ʌ/ indicated a significant main effect of condition, $F(2, 26) = 5.45$, $p = .011$. Post hoc comparisons further indicated a greater duration difference for the slow versus loud ($p = .008$) condition. For the vowel pair /æ–ɛ/, the main effect of group was significant, $F(2, 14) = 4.44$, $p = .032$, with post hoc comparisons indicating a greater duration difference for the MS group compared with the PD group ($p = .039$). For /i–ɪ/, effects were found to be significant for group, $F(2, 14) = 9.07$, $p = .003$; condition, $F(2, 26) = 21.2$, $p < .001$; and the Group × Condition interaction, $F(4, 28) = 4.56$, $p = .006$. Post hoc comparisons further indicated that for the control group but not the PD or MS groups, the slow condition was associated with a greater duration difference compared with both the clear ($p = .001$) and loud ($p < .001$) conditions. Finally, for /u–ʊ/, there was a significant effect of condition, $F(2, 26) = 9.77$, $p < .001$. Post hoc testing indicated a greater duration difference for both the clear and slow conditions versus the loud condition ($p < .003$).

In sum, relative to the habitual condition, vowel durations were maximized in the slow condition, followed by the clear and loud conditions, although duration adjustments for the MS and PD groups were less robust than for controls. Temporal distinctiveness of peripheral–nonperipheral vowel pairs also tended to be maximized in the slow condition.

Vowel Spectral Measures

Vowel space area—Figures 3 and 4 report average F1 × F2 coordinates for peripheral and nonperipheral vowels for the PD and MS groups. Vowel space area may be inferred from lines connecting vowel coordinates. Data for male (upper panel) and female participants (lower panel) are reported in each figure. For peripheral vowel space area shown in Figure 3, a significant effect of group was observed, $F(2, 14) = 7.23$, $p = .002$. Post hoc testing indicated that vowel space area for the PD group was reduced relative to controls ($p = .002$) and, surprisingly, for controls relative to the MS group ($p = .037$). There was also a significant effect of condition, $F(2, 26) = 15.02$, $p < .001$, with larger peripheral vowel space areas in the clear condition compared with both the loud ($p < .001$) and slow ($p < .001$) conditions. Individual speaker data further indicated that 13 of 15 control, 9 of 13 PD, and 6 of 11 MS speakers had the largest peripheral vowel space area in the clear condition relative to the other three conditions. Two controls, four PD speakers, and two MS speakers had the largest peripheral vowel space area in the slow condition, whereas the loud condition was associated with the largest peripheral vowel space area for three speakers with MS. In addition, 38 of 39 speakers increased vowel space area for the clear condition relative to the habitual condition, and 35 of 39 speakers increased vowel space area for the slow condition relative to the habitual condition (i.e., two control and two PD speakers were the exceptions). For the loud condition, 26 of 39 speakers increased peripheral vowel space relative to the habitual condition (i.e., five control, four PD, and four MS speakers were the exceptions).

The statistical analysis for nonperipheral vowel space area shown in Figure 4 also indicated a significant effect of group, $F(2, 14) = 10.00$, $p = .002$. Post hoc comparisons indicated smaller nonperipheral vowel space areas for both the MS and PD groups versus controls ($p < .023$). The condition effect also was significant, $F(2, 26) = 23.44$, $p < .001$. Post hoc testing indicated that the clear and slow conditions were associated with a significantly larger nonperipheral vowel space area compared with the loud condition ($p = .013$). Inspection of individual speaker data further revealed that 12 of 15 control, 11 of 13 PD, and 6 of 11 MS speakers produced the largest nonperipheral vowel space area in the clear condition relative to the other three conditions. In addition, three controls, two PD, and three MS speakers produced the largest nonperipheral vowel space area in the slow condition, whereas the loud condition was associated with the largest nonperipheral vowel space areas for three speakers with MS. All speakers increased nonperipheral vowel space area for the clear condition relative to the habitual condition, and 34 of 39 speakers increased vowel space area for the slow condition relative to the habitual condition (i.e., three PD and two

MS speakers were exceptions). For the loud condition, 30 of 39 speakers increased nonperipheral vowel space relative to the habitual condition (i.e., four control, two PD speakers, and three MS speakers were exceptions).

Table 6 reports the mean percentage change (i.e., increase) in peripheral and nonperipheral vowel space area for the clear, loud, and slow conditions relative to the habitual condition. On average, Table 6 indicates a relatively greater increase in nonperipheral vowel space area, although there is substantial variability within groups and conditions. Within conditions, Table 6 also indicates a smaller percentage increase in vowel space area for the MS and PD groups, compared with controls.

Euclidean distance from habitual centroid—Euclidean distance from habitual centroid measures were characterized descriptively following Turner et al. (1995). This descriptive approach to the data also helped constrain the number of statistical tests. Table 7 reports the mean percentage change in Euclidean distance from habitual centroid for individual vowels produced in the clear, loud, and slow conditions relative to distances for the habitual condition. Standard deviations are reported in parentheses. Positive values indicate increased Euclidean distances regarding distances for the same vowel produced in the habitual condition, whereas negative values indicate reduced Euclidean distances regarding the habitual condition.

There are several observations to be made from this table. First, the fact that the majority of percentages are positive indicates that vowels were more peripherally located in F1 × F2 space for the clear, loud, and slow conditions versus their position in F1 × F2 space for the habitual condition. By inference, with a few exceptions, all peripheral vowels and all nonperipheral vowels were contributing, at least to some extent, to changes in vowel space area for the clear, loud, and slow conditions. A second observation is that within groups, mean percentages for nonperipheral vowels tend to be much larger for /ɛ/ and /ɪ/ compared with /ʌ/ and /ʊ/. An exception is the slow condition for controls. This trend indicates that front vowels contributed proportionately more to the increase in nonperipheral vowel space area for the clear, loud, and slow conditions. In contrast, mean percentages for the four peripheral vowels tend to be more similar within conditions, although in a few instances the front vowels /æ/ and /i/ are associated with somewhat larger percentages than /ɑ/ or /u/ (i.e., control clear, control loud, PD clear). These exceptions aside, all peripheral vowels apparently contributed about the same to increases in vowel space area for the clear, loud, and slow conditions.

Finally, within speaker groups, percentages for a given vowel may be compared across conditions. For example, for the PD group, the greater percentage for /ɑ/ in the clear condition (i.e., *M* = 16%, *SD* = 15%) versus the loud (i.e., *M* = 9%, *SD* = 10%) or slow (i.e., *M* = 11%, *SD* = 15%) conditions indicates that /ɑ/ was most peripherally located in F1 × F2 space in the clear condition. For all speaker groups, percentages for peripheral vowels tend to be greatest in the clear condition. A similar trend held for nonperipheral vowels, although there were several exceptions (e.g., greater mean percentage for MS groups /ɛ/ in the loud condition compared with the clear or slow condition).

Absolute angle difference—Statistical analyses for absolute angle difference measures were not significant. This issue is considered further in the Discussion.

Lambda—Figure 5 reports mean lambda measures for peripheral and nonperipheral vowels. Error bars are not shown so that differences among condition may be more easily observed. The relative contribution of F1 and F2 to lambda may be inferred from the length of black and gray shading within a given bar. Figure 5 indicates that F2, and by inference the front–back dimension, contributes more to lambda than does F1 or high–low tongue position. For peripheral vowels shown in the upper panel of Figure 5, the statistical analysis indicated a significant effect of condition, $F(2, 26) = 14.90$, $p < .001$. Post hoc comparisons indicated smaller lambda values in the slow condition compared with both the clear and loud conditions ($p < .001$). Figure 5 further suggests that, on average, peripheral lambda measures were largest in the clear condition followed by the loud, habitual, and slow conditions. Inspection of individual speaker data revealed that 9 of 15 controls, 4 of 13 PD, and 7 of 11 MS speakers produced the largest peripheral lambda values in the clear condition. Further, 4 of 15 controls, 5 of 13 PD, and 2 of 11 MS speakers produced the largest lambda measures in the loud condition relative to all other conditions.

For nonperipheral vowels, there also was a main effect of condition, $F(2, 26) = 14.90$. $p < .001$. Post hoc comparisons indicated that the slow condition had smaller lambda values compared with both the clear and loud ($p < .001$) conditions. The Group × Condition interaction also was significant, $F(4, 28) = 3.63$, $p = .01$. Post hoc comparisons indicated that the control group had smaller nonperipheral lambda values in the slow condition compared with both the clear and loud conditions ($p < .001$), whereas the PD group had significantly smaller nonperipheral lambda values for the slow condition compared with the clear condition ($p = .017$). Inspection of individual speaker data revealed that 11 of 15 controls and 9 of 13 PD speakers produced the largest nonperipheral lambda values in the clear condition. Furthermore, 2 of 13 PD speakers, 2 of 15 control speakers, and 7 of 11 MS speakers produced the largest lambda values in the loud condition relative all other conditions. It is interesting to note, as shown in the lower panel of Figure 5, that nonperipheral lambda values for the MS group tended to be maximized in the loud condition.

Peripheral–nonperipheral spectral distance—Figure 6 reports mean spectral distances for peripheral–nonperipheral vowel pairs. Larger distance measures indicate greater spectral distinction for a given vowel pair. Standard deviations are not reported in this figure to facilitate visual clarity as well as in light of the fact that few of the statistical analyses were significant. Indeed, the only significant finding in the statistical analysis was a main effect of condition for /i–ɪ/, $F(2, 26) = 3.69$, $p = .0388$ (shown in the upper left panel of Figure 6). Post hoc pairwise comparisons further investigating this main effect were not significant. Figure 6 suggests several instances of reduced or similar spectral distances for peripheral–nonperipheral vowel pairs in the clear, loud, and slow conditions relative to the habitual condition. This trend is perhaps most evident for /æ–ɛ/ and is likely due to the greater relative change in the size of the nonperipheral vowel space area compared with peripheral vowel space area (see Table 6).

In summary, peripheral vowel space area was maximized in the clear condition. Euclidean distance from habitual centroid measures indicated that /ɑ/, /æ/, /i/, and /u/ all tended to occupy more peripheral positions in F1 × F2 space and thus were contributing to the increased vowel space area for the clear condition. Peripheral vowels also were associated with significantly greater dynamic formant movement in both the clear and loud conditions versus the slow condition. For nonperipheral vowels (/ɛ, ʊ, ɪ, ʌ/), the clear and slow conditions were associated with a significantly larger vowel space area compared with the loud condition. Euclidean distance from habitual centroid measures further suggested that front vowels were largely responsible for adjustments in nonperipheral vowel space area. Nonperipheral vowels for the PD group also were associated with significantly greater dynamic formant movement in the clear condition compared with the slow condition. Although not statistically significant, there was a trend for nonperipheral vowels produced by the MS group to have the greatest dynamic formant movement in the loud condition.

Discussion

The primary purpose of the current study was to compare the impact of rate reduction, increased vocal intensity, and clear speech on spectral and temporal characteristics of vowels produced by individuals with PD and MS. These types of comparative studies are lacking, for dysarthria as well as for neurologically typical talkers (but see Wohlert & Hammen, 2000). Results indicated that the clear condition simultaneously reduced articulatory rate and increased vocal intensity for sentences produced by speakers with PD and MS, although the adjustments were more modest than those for either the slow or loud conditions. In addition, the clear condition generally had the most robust and consistent effect on spectral characteristics of both peripheral and nonperipheral vowels. Spectral and temporal distinctiveness for peripheral–nonperipheral vowel pairs generally did not differ for the clear, loud, and slow conditions, although temporal distinctiveness for some vowels pairs was maximized in the slow condition. The remainder of the discussion considers these results in more detail as well as their implications.

It is first worth reiterating that rate reduction, an increased vocal intensity, and clear speech were not studied using a training paradigm. Rather, as in previous studies from our lab and other labs (e.g., Darling & Huber, 2011; Kleinow et al., 2001; McHenry, 2003; Mefferd & Green, 2010; Tjaden & Wilding, 2011), the clear, loud, and slow conditions were elicited using magnitude production. Results therefore should not be compared with dysarthria studies of rate reduction or increased loudness that have used long-term training paradigms, and generalizations to clinical practice should be made with the appropriate degree of caution (see Yorkston, Hakel, et al., 2007, for a discussion of levels of evidence concerning global dysarthria treatment techniques).

Duration and SPL

Not all speakers with dysarthria can apparently slow articulation rate on command (Van Nuffelen et al., 2010). However, on average, the PD and MS groups reduced articulation rate by approximately 28% in the slow condition, whereas the control group reduced articulation rate by an average of 45%. This magnitude of rate reduction as well as the tendency for speakers with MS and PD to voluntarily reduce their rate somewhat less than neurologically typical speakers agrees with findings from previous studies (e.g., Tjaden & Wilding, 2004). Although vowel durations also tended to be maximized in the slow condition, this trend was statistically significant only for controls. However, even the more limited lengthening of vowels in the slow condition for the MS and PD groups apparently afforded sufficient time for these speakers to achieve less centralized or more canonical vocal tract configurations for at least some vowels relative to the habitual condition. This suggestion follows from vowel space area measures as well as the Euclidean distance from habitual centroid measures for the slow condition.

It also should be kept in mind that speech duration measures were composites calculated across the 25 Harvard sentences. A token-by-token analysis of sentences is beyond the scope of the current study. However, we agree with Van Nuffelen et al. (2010) that the extent to which speakers with a variety of neurological diagnoses and dysarthrias can maintain a slowed rate (or increased loudness or clear speech) after being instructed only once deserves further study. Varying degrees of cognitive impairment common in progressive neurological diseases like MS and PD might further be expected to impact these kinds of maintenance effects above and beyond any effects resulting from dysarthria.

The magnitude production paradigm also was successful in eliciting an increased vocal intensity for the loud condition. Mean SPL increased by about 7 dB for the MS and PD groups in the loud condition relative to the habitual condition, whereas mean SPL increased by approximately 9 dB for controls. This magnitude of increase in vocal intensity also is consistent with other dysarthria studies stimulating an increased loudness (e.g., Darling & Huber, 2011; Dromey, 2000). Although some dysarthria studies report adjustments in articulatory rate or segment durations, typically in the form of a slowed rate, when vocal intensity is increased (see review in C. M. Fox, Morrison, Ramig, & Sapir, 2002), speech durations in the current study were not significantly different for the habitual and loud conditions. However, inspection of individual speaker data indicated that four speakers with PD had the fastest articulation rate in the loud condition compared with the other three conditions. Each of these speakers also had an accelerated habitual articulation rate relative to the control group mean reported in Table 3. Further increases in articulation rate for these individuals with PD might be undesirable because segmental integrity is presumably more difficult or effortful to maintain at a faster-than-habitual rate (Weismer, Laures, Jeng, Kent, & Kent, 2000). Alternatively, the increased neuromotor drive associated with an increased vocal intensity, which in turn is thought to explain increased articulatory speeds and distances for loud speech (see McClean & Tasko, 2003; Wohlert & Hammen, 2000), might offset any challenges to maintaining segmental integrity related to the accelerated speech tempo. Studies investigating covariation of vocal intensity and a faster-than-normal articulation rate in dysarthria as well as the relationship to habitual articulation rate would help to evaluate these suggestions.

To date, production studies investigating clear speech in dysarthria have mostly focused on PD. In Dromey's (2000) study, hyperarticulate speech was associated with a 24% increase in utterance duration for "Buy Bobby a puppy" relative to habitual speech as well as an increase in vocal intensity of about 5 dB. Goberman and Elmer (2005) also found that speakers with PD slowed articulation rate by 8% for a reading passage when prompted to use clear speech. Vocal intensity was not measured. In the current study, articulatory rate in the clear condition for both the PD and MS groups was reduced by approximately 20% relative to the habitual condition. Mean SPL for the clear condition also increased by an average of 3 to 5 dB across all groups. The current results therefore replicate findings for speakers with PD reported in Dromey (2000) and Goberman and Elmer (2005) and extend these clear speech effects to speakers with MS. The current results further suggest the feasibility of using clear speech therapeutically for targeting both an accelerated articulatory rate and reduced vocal intensity in dysarthria, as was noted for the current speakers with PD.

The fact that the instructions for eliciting clear speech mentioned the possibility of a reduced rate and increased SPL may have contributed to the simultaneous adjustments in vocal intensity and rate. However, the same types and magnitudes of duration and intensity variation have been reported in clear speech studies that do not explicitly mention rate or intensity in the clear speech instructions (see review in Smiljanić & Bradlow, 2009). Indeed, there is no standard cue or instruction for eliciting clear speech. Dromey (2000), for example, instructed speakers with PD to “exaggerate the movements of their mouth,” whereas Goberman and Elmer (2005) instructed speakers with PD to “produce as clearly as possible, as if someone is having trouble hearing or understanding you.” Beukelman et al. (2002) simply asked speakers with dysarthria secondary to traumatic brain injury to “speak clearly.” As an aside, Ferguson (2004) has suggested that more specific instructions than “speak clearly” may be required to maximize clear speech effects. The nature of the instruction for eliciting clear speech has been shown to yield acoustic adjustments of varying magnitude in neurologically healthy talkers, including adjustments in global speech timing and SPL (Lam et al., 2012). A follow-up perceptual study from our lab further suggests that the acoustic adjustments associated with different clear speech instructions are perceptually meaningful (Lam & Tjaden, in press). Similar studies in dysarthria would help to optimize clear speech training or treatment programs for dysarthria.

Peripheral and Nonperipheral Vowel Spectral Measures

Given current understanding of segmental articulatory behavior in dysarthria, therapeutic techniques that increase movement speeds and amplitudes as well as those promoting increased movement distinctiveness would seem desirable, at least when treatment is focused on articulatory subsystem impairment (Hustad & Weismer, 2007). Movement speed, as inferred from acoustic measures of F2 slope (Yunusova et al., 2012), was not of interest in the current study, as F2 slope measures are most appropriate for vocalic events, such as diphthongs, which require relatively large changes in vocal tract shape. Vowel space area measures, however, allow for inferences regarding articulatory position distinctiveness among peripheral and nonperipheral vowels as well as overall vowel centralization (Weismer et al., 2012). On average, rate reduction, increased vocal intensity, and clear speech each were associated with an increase in both peripheral and nonperipheral vowel space area relative to the habitual condition. The magnitude of the increase was most robust for the clear condition, however (Table 6). Variations in the size of the vowel space area could be the result of centralization for some vowels while other vowels move to more peripheral locations in F1 × F2 space (i.e., away from a neutral vocal tract configuration). To investigate this possibility, we obtained Euclidean distance from habitual centroid measures. We also obtained absolute angle difference measures to explore potential rotational differences in the position of vowels in F1 × F2 space. It seems plausible, for example, that vowels in the loud condition might occupy a different location in F1 × F2 space in comparison to the clear or slow conditions if the effects of jaw lowering on F1 for loud speech are disproportionate relative to adjustments in tongue advancement as reflected in F2.

Front nonperipheral vowels contributed most to increases in nonperipheral vowel space area, whereas the four peripheral vowels tended to contribute more equally to increases in peripheral vowel space area (Table 5). With a few exceptions, Euclidean distance measures further indicated that individual peripheral and nonperipheral vowels were most peripherally located in F1 × F2 space in the clear condition. The nonsignificant results for absolute angle difference measures further indicated that the clear, loud, and slow conditions did not differentially affect the rotational position of vowels in F1 × F2 space. In other words, the clear, slow, and loud conditions were associated with similar degrees of relative change in the high–low tongue dimension as well as the front–back tongue dimension. Taken together, results for vowel space area and Euclidean distance indicate that the clear condition maximized spectral distinctiveness of both peripheral vowels and nonperipheral vowels and also resulted in vowels being most peripherally located in F1 × F2 space (i.e., furthest from operationally defined neutral vocal tract configuration). Given the relationship between vowel space area and intelligibility reported in at least some studies (see discussion in Weismer et al., 2012), a strong prediction is that intelligibility also would be maximized in the clear condition.

Peripheral and nonperipheral vowel space areas for the PD group were reduced relative to controls, as was non-peripheral vowel space area for the MS group. These results provide further support for the idea that vowel centralization is a general characteristic of dysarthria (Weismer et al., 2012). An unexpected finding was that peripheral vowel space area for the MS group was statistically larger compared with the control group. On average, peripheral vowel space area for the MS group was greater than controls in both loud (MS mean = 329060 Hz^2; control mean = 292858 Hz^2) and slow conditions (MS mean = 339756 Hz^2; control mean = 324849 Hz^2) but not the clear condition (MS mean = 367968 Hz^2; control mean = 409631 Hz^2). Even for the habitual condition, both peripheral and nonperipheral vowel space areas for the MS group were slightly larger compared with the control group. The implication is that, as a whole, vowel production for the MS group was largely intact. By inference, the relatively poorer scaled estimates of severity (Table 2) for these speakers likely reflect deviancies in voice and prosody rather than articulatory variables. Similar statements apply to the SIT scores for these speakers. Even the speakers with PD had relatively mild dysarthria, as suggested by their SIT scores. Studies involving more severely impaired speakers are needed to determine the generaliz-ability of results.

Finally, formant movement over time is important for vowel identity (e.g., Assmann & Katz, 2005; Hillenbrand & Nearey, 1999). With the exception of nonperipheral vowels produced by the MS group, for whom the loud condition maximized dynamic formant movement, dynamic formant movement of vowels also was maximized in the clear condition. It is interesting to note that the slow condition was associated with a reduced degree of dynamic formant frequency change relative to habitual levels (Figure 5). Reduction in dynamic formant frequency variation at a slower-than-normal rate could help to explain why rate reduction is not consistently associated with improved intelligibility in dysarthria. Because the lambda measure samples formant movement over only two discrete time points and also is more strongly influenced by spectral change in F2, it is possible that dynamic formant metrics that more densely sample formant frequency time histories or metrics that are computed separately for F1 and F2 would yield different results (see R. A. Fox & Jacewicz, 2009). Future studies can now build on the current findings to investigate this issue both in monophthongs as well as diphthongs, which are particularly well suited for studies of vowel formant dynamics.

Peripheral–Nonperipheral Spectral and Temporal Distinctiveness

Measures of spectral and temporal distinctiveness for peripheral–nonperipheral vowel pairs generally did not differ for the clear, loud, and slow conditions. Lam et al. (2012) suggested that any speaking condition–related enhancement in distinctiveness for peripheral–nonperipheral vowel pairs is subtle, a finding also supported by Kim (2011) in a recent study investigating the impact of increased vocal intensity on spectral distinctiveness of peripheral–nonperipheral vowel pairs. The failure for spectral distinctiveness of peripheral–nonperipheral vowel pairs to be enhanced in the clear, loud, and slow conditions is likely explained by the proportionately greater increase in vowel space area and, by inference, the more peripheral location of vowels in F1 × F2 space for nonperipheral vowels compared with peripheral vowels (see Table 4). Indeed, in some instances, spectral distinctiveness for peripheral–nonperipheral vowel pairs was reduced in the clear, loud, or slow conditions relative to habitual levels. This trend was most evident for /æ–ɛ/, which is of concern given that these vowels are frequently confused (Neel, 2008). With the exception of the slow condition for some peripheral–nonperipheral pairs, duration also was not reliably used by speakers to enhance peripheral–nonperipheral vowel distinction. Thus, global therapy techniques primarily enhance vowel acoustic distinctiveness within the broader categories of peripheral and nonperipheral vowels but not across the categories.

In conclusion, clear speech appears to hold the most promise for enhancing (vowel) segmental articulation in dysarthria, although for at least some speakers with MS, an increased vocal intensity maximized dynamic characteristics of vowels. An explanation for why spectral distinctiveness for peripheral and nonperipheral vowels was maximized in the clear condition may relate to increased neuromotor drive and articulatory effort associated with speaking clearly (Perkell, Zandipour, Matthies, & Lane, 2002; Searl & Evitts, 2012; Wohlert & Hammen, 2000). In contrast, although increased vocal loudness also is reportedly associated with an overall increase in neuromotor drive (Wohlert & Hammen, 2000), the focus is on increasing movement amplitude in the phonatory mechanism. Rate reduction presumes that increased amplitudes will arise simply as the result of increased duration. Future studies are needed to determine whether the current effects hold for phonemes other than monophthongal vowels as well as in designs using training paradigms rather than stimulation. The perceptual consequences of the acoustic adjustments reported in the current study also are an important topic for future research.

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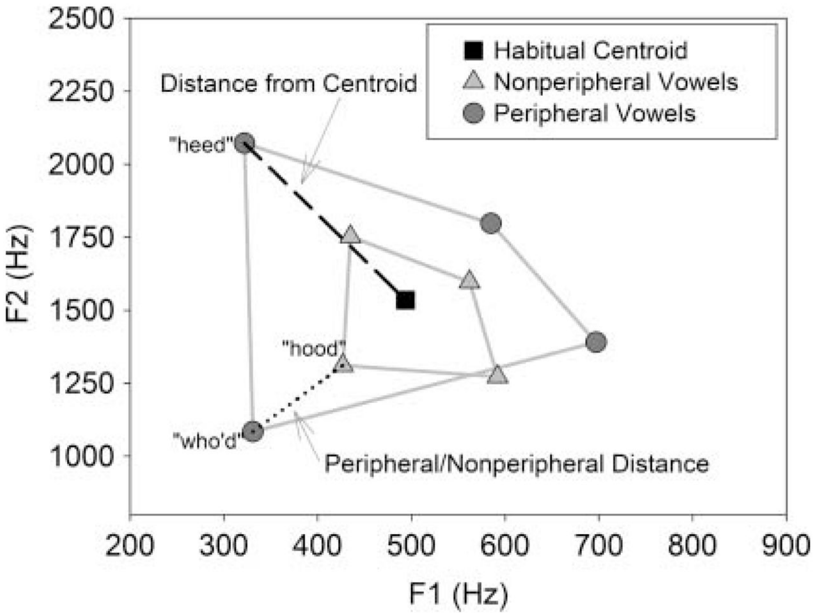

Figure 1.

A schematic of the peripheral vowel space area, nonperipheral vowel space area, and Euclidean distance from habitual centroid for the vowel /i/. Peripheral–nonperipheral (Euclidean) distance for /u–ʊ/ also is illustrated.

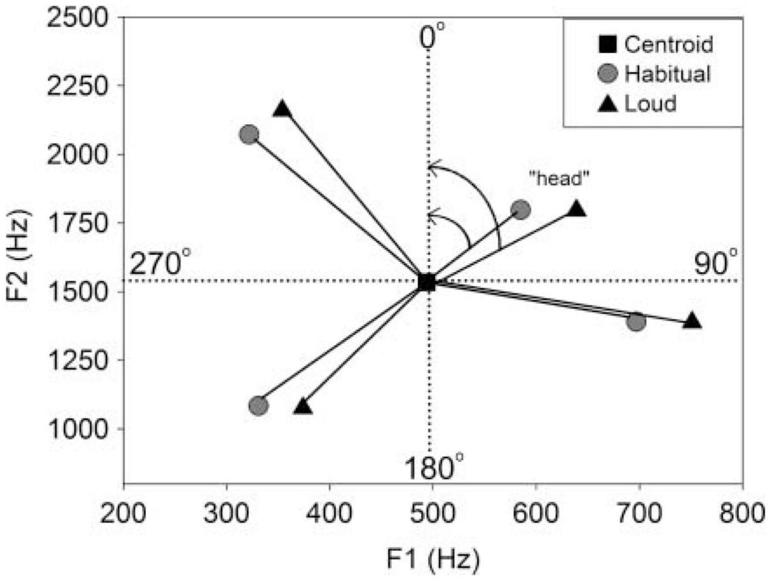

Figure 2.

A schematic illustrating the absolute angle difference measure. For simplicity, angles for the vowel /ɛ/ are shown in the habitual and loud conditions. For each speaker, condition, and vowel, the angle formed by the F1 × F2 coordinate as it bisects the habitual centroid was calculated.

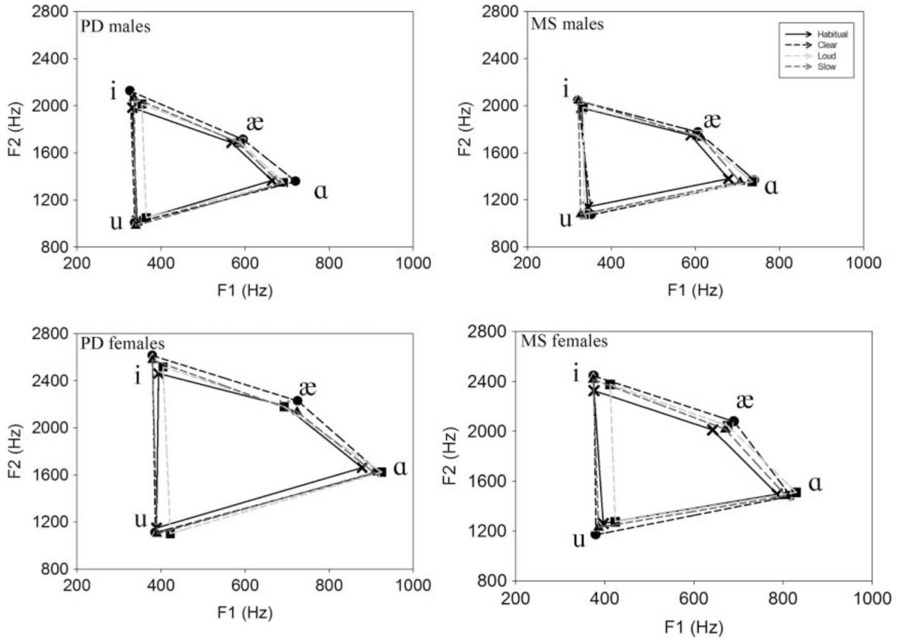

Figure 3.

Mean F1 × F2 coordinates for peripheral vowels produced by the PD and MS groups. Vowel space area may be inferred from lines connecting vowel coordinates. Data for male speakers are reported in the upper panels, and data for female speakers are reported in the lower panels.

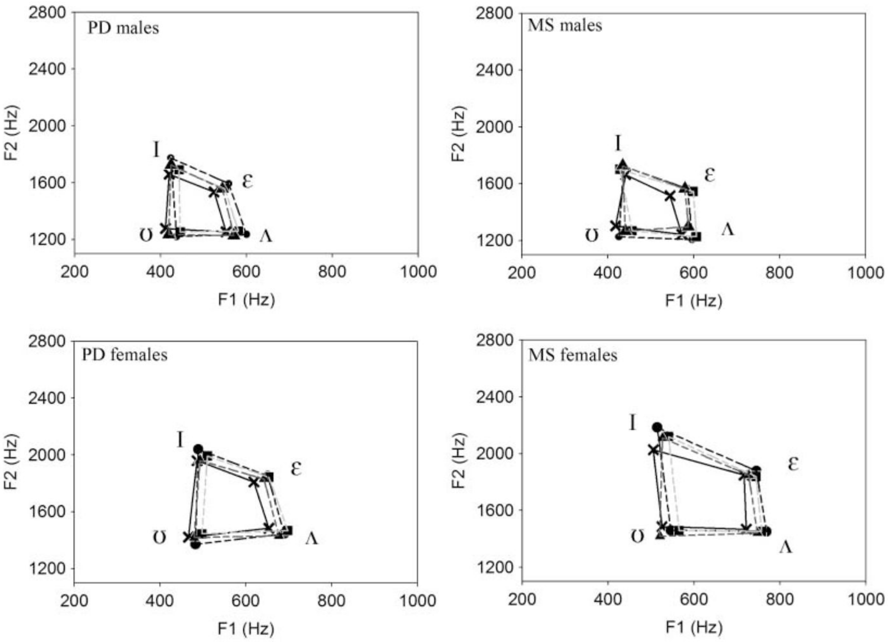

Figure 4.

Mean F1 × F2 coordinates for nonperipheral vowels produced by the PD and MS groups. Vowel space area may be inferred from lines connecting vowel coordinates. Data for male speakers are reported in the upper panels, and data for female speakers are reported in the lower panels.

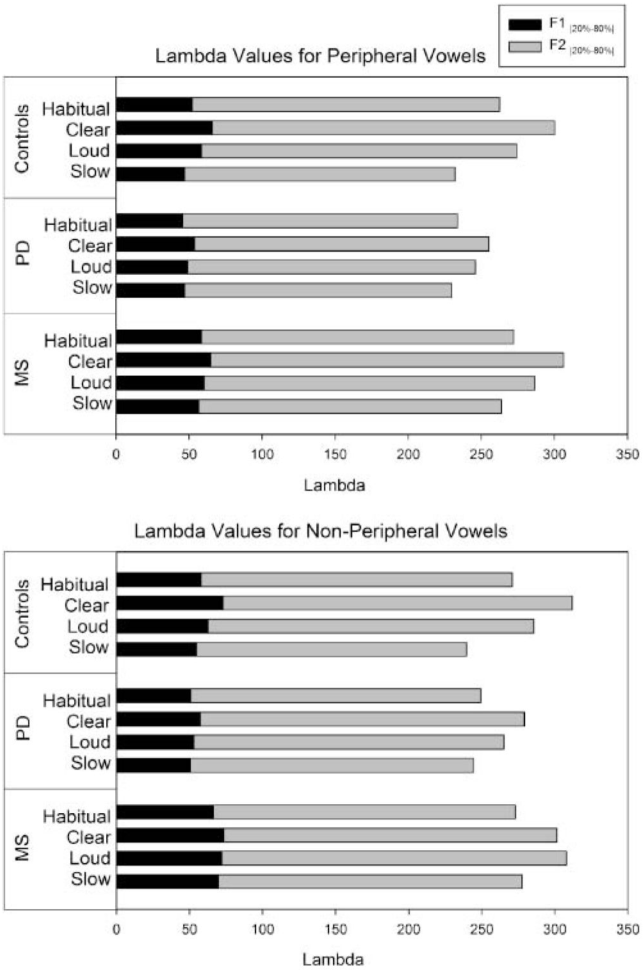

Figure 5.

Mean lambda measures reflecting dynamic formant movement for peripheral and nonperipheral vowels. Error bars are not shown so that differences among condition may be more easily observed. The relative contribution of F1 and F2 to lambda may be inferred from the height of black and gray shading within a given bar.

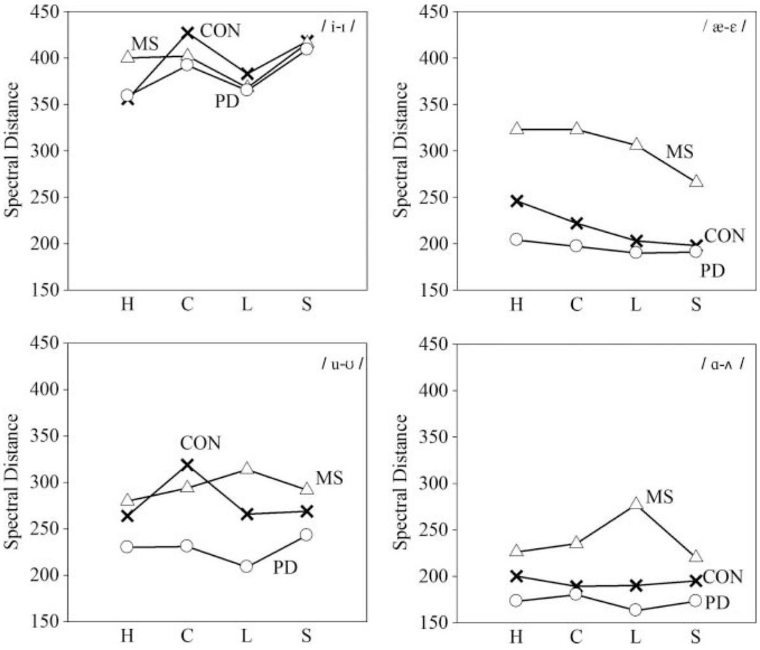

Figure 6.

Mean spectral distances (i.e., Euclidean distances) for peripheral–nonperipheral vowel pairs are reported as a function of group and condition. Larger distance measures indicate greater spectral distinction for a given vowel pair. CON = control; H = habitual; C = clear; L = loud; S = slow.

Table 1

Speaker characteristics for participants with Parkinson’s disease (PD).

Subject code	Gender	Age	Years postdiagnosis	Sentence intelligibility score (%)	Scaled speech severity
PD 01	F	76	20	84	0.85
PD 02	F	78	3	95	0.36
PD 04	F	48	11	90	0.54
PD 05	F	74	2	87	0.66
PD 06	F	75	5	90	0.62
PD 08	F	63	2	89	0.26
PD 01	M	76	12	87	0.46
PD 02	M	65	8	89	0.50
PD 03	M	58	13	89	0.65
PD 04	M	55	5	92	0.10
PD 06	M	66	3	91	0.20
PD 07	M	67	32	90	0.63
PD 08	M	78	4	90	0.80
M (*SD*)		68 (9)	9 (8)	89 (3)	0.51 (0.23)

Note. Intelligibility scores from the Sentence Intelligibility Test (SIT) reflect judgments of 10 inexperienced listeners. Scaled estimates of severity were provided by three speech–language pathologists (SLPs) using a computerized Visual Analog Scale (VAS) adapted from Cannito et al. (1997). SLPs were instructed to judge speech severity on the basis of voice, resonance, articulatory precision, and prosody without regard for intelligibility.

Table 2

Speaker characteristics for participants with multiple sclerosis (MS).

Subject code	**Gender**	**Disease course**	**Age**	**Years postdiagnosis**	**Sentence intelligibility score (%)**	**Scaled speech severity**
MS 02	F	PP	66	18	95	0.92
MS 03	F	PP	58	2	93	0.61
MS 04	F	SP	62	9	95	0.77
MS 06	F	RR	54	25	89	0.94
MS 11	F	PP	56	15	90	0.59
MS 17	F	RR	47	18	93	0.62
MS 01	M	PP	53	25	83	0.81
MS 04	M	PP	63	22	91	0.82
MS 05	M	SP	55	6	92	0.54
MS 07	M	RR	48	4	89	0.47
MS 09	M	RR	47	8	93	0.76
M (*SD*)			55 (7)	13 (8)	91 (3)	0.71 (0.16)

Note. Intelligibility scores from the SIT reflect judgments of 10 inexperienced listeners. Judgments of scaled severity were performed by three SLPs using a computerized VAS adapted from Cannito et al. (1997). SLPs were instructed to judge speech severity on the basis of voice, resonance, articulatory precision, and prosody without regard to intelligibility. PP = primary progressive; SP = secondary progressive; RR = relapsing remitting.

Table 3

Means (and standard deviations) for articulatory rate and sound pressure level as a function of group and condition.

Group	Habitual	Clear	Loud	Slow
Articulatory rate (syllables per second)				
Control	3.7 (0.5)	2.4 (0.4)	3.3 (0.6)	2.0 (0.7)
PD	4.0 (0.6)	3.1 (0.7)	3.9 (0.7)	2.8 (0.7)
MS	3.4 (0.7)	2.7 (0.8)	3.2 (0.7)	2.5 (0.7)
Sound pressure level (dB SPL)				
Control	74 (2.8)	79 (4.4)	85 (4.2)	74 (4.0)
PD	72 (2.4)	75 (3.6)	79 (3.0)	72 (4.6)
MS	71 (2.6)	75 (3.1)	78 (2.3)	71 (5.0)

Table 4

Means (and standard deviations) for vowel duration (in milliseconds) as a function of condition and group.

	Peripheral vowels				
Group	**/ɑ/**	**/æ/**	**/i/**	**/u/**	**All peripheral**
Control	155 (54)	165 (46)	108 (40)	156 (54)	140 (54)
MS	161 (68)	164 (65)	114 (63)	147 (90)	142 (74)
PD	160 (57)	172 (47)	104 (45)	144 (67)	139 (60)
			Clear		
Control	213 (65)	220 (63)	183 (65)	265 (102)	214 (79)
MS	203 (105)	206 (113)	161 (92)	217 (117)	191 (107)
PD	193 (82)	197 (64)	143 (71)	196 (104)	176 (83)
			Loud		
Control	197 (66)	214 (52)	138 (49)	181 (84)	176 (69)
MS	204 (92)	211 (90)	145 (74)	211 (133)	185 (100)
PD	180 (68)	196 (53)	113 (48)	141 (65)	152 (67)
			Slow		
Control	334 (197)	335 (187)	333 (229)	366 (215)	340 (210)
MS	291 (214)	281 (243)	219 (178)	273 (198)	259 (207)
PD	221 (83)	222 (73)	164 (73)	223 (118)	200 (90)

	Nonperipheral vowels				
Group	**/ʌ/**	**/ɛ/**	**/ɪ/**	**/ʊ/**	**All nonperipheral**
			Habitual		
Control	114 (40)	116 (47)	94 (43)	83 (31)	105 (44)
MS	116 (60)	120 (67)	91 (47)	87 (47)	107 (60)
PD	114 (44)	111 (45)	88 (36)	84 (33)	101 (43)
			Clear		
Control	165 (61)	165 (64)	143 (62)	119 (48)	152 (63)
MS	146 (77)	148 (85)	125 (77)	112 (67)	136 (80)
PD	140 (59)	136 (60)	111 (51)	106 (45)	126 (57)
			Loud		

Group	Peripheral vowels				
	/ɑ/	/æ/	/i/	/u/	All peripheral
Control	154 (56)	148 (56)	128 (48)	111 (38)	138 (53)
MS	166 (96)	152 (83)	125 (61)	114 (56)	142 (79)
PD	136 (60)	128 (55)	109 (47)	96 (32)	120 (53)
			Slow		
Control	283 (206)	294 (238)	246 (200)	248 (205)	272 (217)
MS	203 (157)	207 (189)	176 (151)	155 (126)	190 (164)
PD	159 (70)	160 (76)	132 (70)	118 (47)	146 (71)

Table 5

Means (and standard deviations) for duration differences (in milliseconds) between the peripheral and nonperipheral vowel pairs.

Group	Habitual	Clear	Loud	Slow
		/ɑ–ʌ/		
Control	40 (13)	48 (17)	43 (18)	**60** (42)
MS	44 (36)	63 (54)	38 (21)	**93** (99)
PD	47 (9)	56 (20)	44 (14)	**62** (20)
		/æ–ɛ/		
Control	48 (19)	55 (18)	**66** (16)	56 (28)
MS	39 (25)	61 (51)	59 (27)	**74** (91)
PD	60 (18)	61 (16)	**69** (18)	62 (16)
		/i–ɪ/		
Control	15 (10)	41 (24)	21 (9)	**87** (61)
MS	27 (28)	38 (21)	25 (24)	**44** (30)
PD	18 (12)	**35** (24)	7 (5)	34 (31)
		/u–ʊ/		
Control	73 (26)	**145** (40)	69 (38)	134 (66)
MS	63 (61)	106 (57)	96 (75)	**117** (63)
PD	58 (26)	95 (52)	45 (12)	**104** (43)

Note. Bolded cells indicate the condition for which the duration difference was magnified.

Table 6

Mean percentage increase (and standard deviations) in vowel space area relative to the habitual condition.

Group	Clear	Loud	Slow
Peripheral vowels			
Control	69 (34)	18 (24)	34 (33)
PD	38 (33)	4 (11)	19 (17)
MS	29 (20)	15 (18)	19 (12)
Nonperipheral vowels			
Control	92 (85)	21 (31)	58 (42)
PD	65 (56)	15 (23)	34 (42)
MS	59 (54)	36 (76)	33 (36)

Table 7

Mean percentage change (and standard deviations) in Euclidean distance from habitual centroid relative to distances for the habitual condition.

	Peripheral vowels											
	Clear				Loud				Slow			
Group	**ɑ**	**æ**	**i**	**u**	**ɑ**	**æ**	**i**	**u**	**ɑ**	**æ**	**i**	**u**
Control	18 (12)	50 (59)	42 (18)	33 (22)	16 (11)	31 (57)	14 (10)	5 (18)	13 (12)	14 (47)	21 (30)	26 (16)
MS	20 (15)	14 (24)	19 (14)	13 (21)	22 (21)	1 (21)	4 (17)	11 (17)	13 (13)	−2 (21)	16 (18)	12 (15)
PD	16 (15)	29 (41)	26 (23)	11 (15)	9 (10)	16 (28)	6 (7)	−6 (12)	11 (15)	5 (16)	17 (16)	7 (10)

	Nonperipheral vowels											
	Clear				Loud				Slow			
Group	**ʌ**	**ɛ**	**ɪ**	**ʊ**	**ʌ**	**ɛ**	**ɪ**	**ʊ**	**ʌ**	**ɛ**	**ɪ**	**ʊ**
Control	19 (18)	109 (114)	80 (50)	39 (31)	9 (14)	78 (59)	27 (39)	10 (24)	22 (17)	56 (74)	36 (35)	45 (29)
MS	11 (11)	39 (36)	58 (31)	17 (19)	9 (10)	49 (52)	27 (42)	8 (17)	−1 (25)	24 (32)	44 (32)	14 (12)
PD	14 (11)	87 (84)	84 (104)	19 (19)	6 (8)	51 (50)	36 (77)	2 (17)	14 (12)	41 (37)	47 (128)	9 (17)