Cueing Mandarin speakers with Parkinson's Disease

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Acoustic and perceptual consequences of speech cues for Mandarin speakers with Parkinson's Disease

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ABSTRACT

Purpose: This study investigated the effects of cueing for increased loudness and reduced speech rate on scaled intelligibility and acoustics of speech produced by Mandarin speakers with hypokinetic dysarthria due to Parkinson's Disease (PD).

Method: Eleven speakers with PD read passages in habitual, loud, and slow speaking conditions. Fifteen listeners rated ease-of-understanding (EOU) of the speech samples on a visual-analog-scale. Effects of the cues on EOU, vocal loudness, pitch range, pause duration and frequency, articulation rate, and vowel space, as well as relationships between EOU gains and acoustic features were analyzed.

Results: EOU increased significantly in the loud condition only. The loud cue resulted in increased intensity and the slow cue resulted both in reduced articulation rate and increased pause frequency. In the loud condition, EOU increased significantly as intensity increased and vowel centralization decreased. In the slow condition, EOU tended to increase as intensity increased and vowel centralization decreased, but did not reach statistical significance.

Conclusion: Cueing for loud speech may yield greater EOU gains than cueing for slow speech in Mandarin speakers with PD. Theoretical and clinical implications are discussed, although further investigations with more participants and a larger range of dysarthria severity are warranted.

Key Words: Mandarin, dysarthria, cues, scaled intelligibility, acoustics, rate, loudness

Introduction

In the United States, Chinese language varieties are, collectively, the third most common language spoken in homes. Over 2.8 million people speak these languages, which include Mandarin and Cantonese (US Census Bureau, 2015). In China and Taiwan, Mandarin is the native language of approximately 1.5 billion people (National Bureau of Statistics of China, 2014; National Statistics of Republic of China [Taiwan], 2014). Within this population, at least 1.7 million people suffer from Parkinson's Disease (PD) at any one time (Chen et al., 2009; Zhang et al., 2005). Some estimate that between 50% to 89% of people with PD will exhibit a speech disorder at some point during the disease progression (Hartelius & Svensson, 1994; Ho, Iansek, Marigliani, Bradshaw, & Gates, 1998; Johnson & Pring, 1990). Speech difficulties in PD are associated with poorer communicative participation outcomes in daily life (McAuliffe, Baylor & Yorkston, 2016). Hence, the number of native speakers of Mandarin (and other related languages) who exhibit hypokinetic dysarthria and restrictions in communicative participation is substantial.

There has been limited investigation, however, into the consequences of speech disorders on intelligibility or on measures of speech acoustics in Mandarin speakers with hypokinetic dysarthria due to PD (henceforth, Mandarin speakers with hypokinetic dysarthria). Even less is known about the effects of speech treatment or cueing techniques commonly implemented to improve intelligibility in these individuals. Consequently, speech-language pathologists (SLPs) working with Mandarin-speaking clients internationally and in the United States have little evidence on which to base their treatment. The current study aimed to examine the effects of two commonly employed behavioral speech modification techniques, cueing for increased loudness and for reduced speech rate, on intelligibility and selected acoustic features of speech produced by Mandarin speakers with hypokinetic dysarthria.

While hypokinetic dysarthria appears to reduce vocal loudness universally, as loudness reductions in individuals with PD have been documented in several languages, including English (e.g., Ramig, Countryman, Thompson, & Horii, 1995; Tjaden & Wilding, 2004), Mandarin (Hsu et al., 2017), and Spanish (Moya-Galé, McAuliffe, & Levy, 2016), dysarthria might also exert language-specific effects on rhythmic features across languages (Liss, Utianski, & Lansford, 2013; Whitehill & Ma, 2014). Mandarin rhythm differs from the stress-timing of English (Pike, 1945), in that Mandarin is a syllable-timed language (Lin & Wang, 2007), with a syllabic structure of consonant-vowel-nasal. Final consonants are optional and can only be nasal (Whitehill & Ma, 2014). Furthermore, every Mandarin syllable has a lexical tone, which is used to convey lexical meaning (Howie, 1976). In other words, fundamental frequency (F_0) variation at the syllabic level is a perceptual cue for segmenting syllables and distinguishing syllabic contrasts in Mandarin. In contrast, F_0 variation at the sentence level is a perceptual cue for conveying intonation in English (Vaissiére, 2005). Thus, F_0 variation at the syllabic level associated with hypokinetic dysarthria in Mandarin is likely to have language-specific effects on intelligibility. The following section considers language-specific, as well as language-universal, effects of the segmental and suprasegmental features of speech sounds on intelligibility associated with hypokinetic dysarthria.

Hypokinetic Dysarthria

Hypokinetic dysarthria is traditionally characterized by reduced loudness, monopitch, short phrases, inappropriate silences, short rushes of speech, harsh or breathy voice, imprecise consonants and vowels (Darley, Aronson, & Brown, 1969), and, in some cases, fast speaking rate

(Duffy, 2013). While these characterizations are generally based on speech produced by speakers of American English with hypokinetic dysarthria, such characteristics have also been noted in speech produced by speakers of Cantonese (Ma, Whitehill, & So, 2010; Whitehill, 2010), a language typologically similar to Mandarin. While the motoric effects of PD might express themselves in these general features, there has been limited research examining the effects of common behavioral speech modification in speakers of tonal languages.

Key Acoustic Features Affecting Intelligibility in Hypokinetic Dysarthria

Considerable evidence suggests that reductions in vowel space area (Feenaughty, Tjaden, & Sussman, 2014; Sapir et al., 2002; Sapir, Spielman, Ramig, Story, & Fox, 2007; Tjaden & Wilding, 2004), consonant articulatory precision (Tjaden & Wilding, 2004), vocal loudness (Cannito et al., 2012; Neel, 2009), pitch range, and articulation rate (Fletcher, McAuliffe, Lansford, Sinex, & Liss, 2017) are linked to reduced intelligibility in English speakers with hypokinetic dysarthria. Thus, the general speech characteristics associated with hypokinetic dysarthria appear to be associated with decreased intelligibility across languages.

However, few studies have examined hypokinetic dysarthria in other languages, including, of relevance here, Mandarin. A recent study of 11 speakers of Mandarin with hypokinetic dysarthria revealed somewhat similar findings to those regarding English speakers with hypokinetic dysarthria. Reductions in vowel space area relative to healthy controls were a key feature of the speakers' dysarthria (Hsu et al., 2017). These results were in partial agreement with findings from studies on Mandarin-speaking young adults with various types of dysarthria, including ataxic, hyperkinetic, spastic, and mixed dysarthrias associated with cerebral palsy (CP; Liu, Tsao, & Kuhl, 2005; Liu, Tseng, & Tsao, 2000). However, in contrast to prior studies of healthy speakers of Mandarin (Chen, Wong, & Wong, 2013) or of Mandarin speakers with CP (Liu et al., 2000; Liu et al., 2005), Hsu et al. (2017) found no association between vowel space area and reduced intelligibility.

Given the tonal languages such as Mandarin use variation in F_0 to signal lexical meaning, it is generally assumed that reductions in pitch variation commonly observed in hypokinetic dysarthria would be strongly linked to decreased intelligibility. However, to date, study findings have been inconsistent. Our previous study (Hsu et al., 2017) found no evidence that reduced syllabic pitch variation was associated with decreased intelligibility in speakers of Mandarin. Similarly, a study of Cantonese speakers with PD showed no correlation between reduced pitch variation at the syllabic level and reduced intelligibility (Whitehill & Wong, 2007). While these PD studies showed no association between pitch variation at the syllabic level and speech intelligibility, an investigation of 30 Mandarin-speaking young adults with three types of dysarthria (hyperkinetic, spastic, and mixed) associated with CP found a relationship between reduced pitch variation and reduced word intelligibility (Jeng, Weismer, & Kent, 2006). The literature has documented variable syllabic pitch variation in speakers with dysarthria in Mandarin and Cantonese, but the relationship between pitch variation and speech intelligibility is not well understood.

While Hsu et al. (2017) reported no clear relationship between speech intelligibility and vowel space area or between intelligibility and syllabic pitch variation in Mandarin speakers with hypokinetic dysarthria, a slower speech rate in this population was found compared to healthy controls. Intelligibility increased significantly as speech rate increased in the speakers with hypokinetic dysarthria. These results seem to contradict the finding of increased intelligibility as speech rate decreases in many English speakers with hypokinetic dysarthria who display a habitually fast speech rate (Tjaden & Wilding, 2004). However, Hsu et al.'s (2017) findings share some commonalities with results from studies on languages other than English. For example, Dutch speakers with hypokinetic dysarthria who exhibit a habitually slow speech rate have been found to increase their intelligibility when cued to speak slowly (Van Nuffelen, De Bodt, Vanderwegen, Van de Heyning, & Wuyts, 2010).

Given the existing literature, it is evident that phonatory and articulatory functions in speech production, as well as global speech timing, are affected in individuals with hypokinetic dysarthria who speak tonal languages; however, the relationship between these speech characteristics and intelligibility is less clear. Kim and Choi's (2017) study of dysarthric speech produced by Korean speakers and by English speakers with hypokinetic dysarthria due to PD reported different acoustic features contributing to intelligibility in the two languages. Intelligibility was significantly associated with vowel space area in the English speakers with hypokinetic dysarthria, whereas a significant association was found for the Korean speakers between intelligibility and 1) vowel space area, 2) voice onset time, and 3) articulation rate. Clinically, the various relationships between acoustic features and intelligibility across languages might have different implications for treatment goals for speakers with dysarthria of various language backgrounds.

The Effects of Increased Loudness and Reduced Rate in Non-Tonal Languages

Cueing techniques for increased loudness and reduced speech rate have been commonly implemented to improve the speech production of individuals with hypokinetic dysarthria (e.g., Tjaden, Sussman, & Wilding, 2014; Tjaden & Wilding, 2004). Cueing for increased loudness improves phonatory and articulatory functions in English speakers with hypokinetic dysarthria (e.g., Fletcher et al., 2017; Sapir et al., 2007; Tjaden & Wilding, 2004). In addition, changes in phonation associated with cues for loudness include increased vocal loudness, higher mean pitch, and greater pitch range in English speakers with hypokinetic dysarthria (Ramig, Bonitati, Lemke, & Horri, 1994; Tjaden & Wilding, 2011a). With regard to articulatory changes, studies (e.g., Sapir et al., 2007) have shown expanded vowel space area, reflecting greater articulatory excursion, when English speakers increase their vocal loudness. While most studies on English speakers with hypokinetic dysarthria have revealed increased vowel space as a result of increased vocal loudness, a study on Spanish-speaking individuals with hypokinetic dysarthria (Moya-Galé et al., 2016) revealed no change in vowel space associated with increased vocal loudness. However, F_0 and vocal loudness significantly increased following the loud cue, suggesting that this cue can result in improved phonatory outcomes. Furthermore, a treatment study on Spanish speakers with hypokinetic dysarthria (Moya-Galé et al., 2018) found that speech intelligibility increased following vocal loudness-based treatment.

As some speakers with hypokinetic dysarthria exhibit a fast speech rate (Duffy, 2013), it is thought that rate reduction cues may be particularly effective in enhancing intelligibility in this group. Surprisingly, Dutch speakers with hypokinetic dysarthria who exhibited a habitually slow speech rate also benefited from speaking slowly on command (Van Nuffelen et al., 2010). Hence, it is possible that rate reduction cues might be helpful for individuals regardless of their habitual speech rate. However, Tjaden and Wilding (2004) reported that following rate reduction cues, intelligibility did not increase significantly in 10 of their 12 English speakers with hypokinetic dysarthria. This finding is consistent with the results of a more recent study of the effects of clear, loud, and slow speech on the intelligibility of 16 English speakers with hypokinetic dysarthria (Tjaden et al., 2014). Thus, the outcomes of rate reduction strategies are perhaps less clear than those of strategies for increasing vocal loudness.

Effects of Increased Loudness and Reduced Speech Rate in Mandarin and Cantonese

There has been limited published work highlighting the outcomes of treatment or behavioral speech modification techniques for individuals with hypokinetic dysarthria who speak languages other than English. In one of the few studies on this topic, Whitehill and Wong (2007) examined the effects of Lee Silverman Voice Treatment LOUD (LSVT LOUD; Ramig, Countryman, O'Brien, Hoehn, & Thompson, 1996; Ramig et al., 1995) on intonation and lexical tone in four Cantonese-speaking individuals with hypokinetic dysarthria. LSVT LOUD is an intensive voice treatment that targets increased vocal loudness primarily in individuals with hypokinetic dysarthria (Ramig et al., 1995). Following the treatment, the Cantonese speakers exhibited increased vocal loudness, mean pitch, and pitch range at the sentence level. These acoustic changes resulted in an improvement in intonation, but not in lexical tone. Whitehill and Wong explain that these Cantonese speakers may have had intact lexical tone in their habitual speech; thus, any changes might not have been perceptually detectable.

While Whitehill and Wong (2007) studied the effects of treatment targeting loudness on the speech of four Cantonese speakers with hypokinetic dysarthria, to the best of our knowledge, there is no published literature on the effects of treatment or cues to speak slowly in Cantonese or Mandarin speakers with hypokinetic dysarthria. However, two Mandarin studies of speech in neurologically healthy individuals have investigated the effects of cueing for slow rate on pitch (Xu, 1998) and vowel and consonant acoustics (Jeng, 2005). Xu (1998) examined the temporal and spectral properties of F_0 in CV syllables at different speaking rates—habitual, fast, and slow, in four neurologically healthy Mandarin speakers. Visual inspection of the temporal (duration) and spectral (slope) features of F_0 showed that F_0 duration was the longest in the slow condition and shortest in the fast condition. However, the peak of the F_0 always occurred in the center of the CV syllables and F_0 slope did not vary as a function of rate, suggesting that the spectral component of the F_0 might not be affected by speaking rate. Similarly, Jeng (2005) examined how various speech rates influenced the temporal quality of vowels and consonants produced by 30 native neurologically healthy Mandarin speakers. These speakers were recorded reading 33 sentences ranging from five to eight syllables at five different speaking rates—fastest, fast, neutral, slow, and slowest. Acoustic analysis revealed that vowel duration was proportional to speech rate, whereas consonant duration was not, suggesting that vowels were more affected by the rate reduction than were consonants—at least in these neurologically healthy Mandarin speakers. Overall, the existing literature provides limited information on the potential effects of cues to reduce rate or increase loudness in Mandarin speakers with hypokinetic dysarthria, and even less is known about any resulting intelligibility outcomes.

Aims and Hypothesis

In summary, increased vocal loudness and/or reduced speech rate are commonly associated with intelligibility gains and acoustic changes in English speakers with hypokinetic dysarthria. However, it is not clear whether the effects of these global speech modification techniques also apply to Mandarin. While speech in hypokinetic dysarthria reflects the deficits in the neural bases of speech production that are shared universally, recent interest has emerged in examining how these shared bases interact with the vast diversity of languages spoken, potentially manifesting themselves differently across languages. It is thus necessary to consider how the deficits seen in hypokinetic dysarthria in English, often the model language, might or might not also be evidenced in other languages. As a first step, empirical assessment of hypokinetic dysarthria across various languages is necessary (Miller & Lowit, 2014; Pinto, Chan, Guimarães, Rothe-Neves, & Sadat, 2017). Furthermore, examinations of various treatment techniques and their effects on intelligibility in different languages are of clinical and theoretical importance (Levy, Moya- Galé, Chang, MacLeod, & Maillart, 2018).

The present study investigated: (1) whether behavioral cues to increase loudness and reduce speech rate would result in significant increases in intelligibility outcomes (relative to habitual speech) of Mandarin speakers with hypokinetic dysarthria, (2) whether such cues would result in significant changes in the acoustic features of vocal loudness, pause duration, pause frequency, articulation rate, vowel space, and syllabic F_0 range, and (3) to what extent the selected acoustic features would account for the variation observed in intelligibility gains.

It was hypothesized that Mandarin speakers with hypokinetic dysarthria would (1) increase their intelligibility in response to cues to increase loudness and to reduce speech rate, with greater gains from the loudness cues (Tjaden & Wilding, 2004), (2) increase their vocal intensity (Tjaden & Wilding, 2004) and F_0 range (Whitehill & Wong, 2007) in response to the loudness cues, and lengthen pause duration, pause frequency, and reduce articulation rate (Tjaden & Wilding, 2011b), and expand their vowel space (Tjaden & Wilding, 2004) in response to the cues to reduce speech rate. Finally, it was hypothesized that (3) intelligibility increases would be significantly associated with increases in vocal loudness (Hsu et al., 2017; Levy, Moya-Galé, Chang, Forrest, & Ramig, 2018) and vowel space, to some extent, based on previous Mandarin studies of neurologically healthy speech (Chen et al., 2013) and dysarthria associated with CP (Liu et al., 2005). However, given the association between speech intelligibility and vowel space in Mandarin speakers with hypokinetic dysarthria (Hsu et al., 2017), it was thought that vowel space might play a lesser role in intelligibility compared to other acoustic features.

Method

This study received ethical approval from the Institute Review Boards (IRB) of (1) Mackay Memorial Hospital, Taipei, Taiwan, (2) National Taiwan University Hospital, Taipei, Taiwan, and (3) Teachers College, Columbia University, New York, United States. All participants provided written consent to participate in this study.

Speakers

Eleven Mandarin-speaking adults with hypokinetic dysarthria associated with PD participated as part of a larger study on speech characteristics and treatment in this population. The speakers included eight males and three females who ranged in age from 62 to 83 years (M = 74, SD = 7) and were members of the public residing in Taipei, Taiwan. On the basis of audio recordings of two conversational monologues (Tjaden & Wilding, 2004) obtained at an initial screening, dysarthria severity was judged and agreed upon by two experienced SLPs who did not treat or test the speakers. The speakers demonstrated mild to severe dysarthria (see Table 1 for biographical details). Other inclusion criteria were that the individuals (1) spoke Mandarin as their primary language, (2) achieved a minimum score of 25/30 on the Mini-Mental State Examination (Folstein, Folstein, & McHugh, 1975), and (3) self-reported adequate hearing for daily communication.

[Insert Table 1 near here]

Listeners

A total of 15 listeners (eight females and seven males) voluntarily participated in this study. All of the listeners were Mandarin-speaking individuals residing in Taipei, Taiwan who ranged in age from 25 to 41 years (*M* = 31, *SD* = 4) and reported no extensive experience interacting with individuals with dysarthric speech or history of speech, language, hearing, learning, or cognitive deficits.

Speech Samples and Recording Procedure

Speakers were recorded reading a Mandarin translation of the Rainbow Passage (Fairbanks, 1960) in habitual, loud, and slow speaking styles. All recordings were conducted in a sound-treated booth at Mackay Memorial Hospital, Taipei, Taiwan by master's-level speech-language pathology students. In the habitual condition, speakers were instructed to speak as they typically would. Magnitude estimation (Tjaden & Wilding, 2004) was used to cue loud and slow speech. That is, in the loud condition, speakers were instructed to speak with a vocal volume twice as loud as their regular volume. In the slow condition, speakers were asked to speak at a rate half as fast as their regular rate. The utterances were produced in habitual, then slow, followed by loud conditions to prevent the carryover effect of loud speech into the other conditions (Fletcher et al., 2017). Prior to reading the experimental passage in the habitual condition, speakers participated in a familiarization task in which they read two 6-word sentences from a different reading passage in their habitual speech. In similar familiarization tasks, they practiced their "loud speech" before the loud condition and their "slow speech" before the slow condition.

A Shure SM10A head-mounted microphone was placed 8 cm away from the speakers' mouths and connected to a Tascam Dr-100 portable digital recorder with a sample rate of 44.1k Hz, and 16-bit resolution on a mono channel. To verify the sound pressure level (SPL) of the stimuli, calibration was performed prior to recording. The standard calibration protocol used in the Speech Perception and Production Lab at Teachers College, Columbia University (Levy, Chang, Ancelle, & McAuliffe, 2017) was implemented in the present study. In brief, a calibration tone was generated at 69 dB by a KORG Auto Chromatic Tuner placed 8 cm from the microphone and recorded on the digital recorder. The experimenter visually noted the SPL of the tone as indicated on a (Galaxy-Audio CM-140) sound level meter. This calibration technique and speakers' consistent mouth-to-microphone distance made it possible to capture and replicate the actual SPL and its changes within the stimuli presented to listeners.

Listening Task and Measurement of Ease-of-Understanding (EOU)

Speech intelligibility was measured by means of listeners' scaled ratings of EOU, a measure commonly implemented in studies of dysarthric speech (Ansel & Kent, 1992; Neel, 2009; Platt, Andrews, Young, & Quinn, 1980; Sidtis, Cameron, Bonura, & Sidtis, 2012; Tjaden & Wilding, 2004; Wenke, Cornwell, & Theodoros, 2010). For example, Tjaden and Wilding (2004) defined intelligibility for listeners as "the ease with which speech (can) be understood, with attention to the precision of articulation" (p. 771).

Fifteen listeners were presented with a total of 231 sentences (7 sentences × 3 conditions × 11 speakers). The seven experimental stimuli (sentences 1, 2, 3, 6, 8, 9, and 16; see Appendix A) were extracted from the 19-sentence passage, which included the target sounds (vowels /i/, /u/, /a/). The presentation of stimuli was programmed using software (Chang & Chang, 2015) customized for this study. The software generated a visual analogue scale and instructed listeners (in Mandarin) to "please rate how easy it is to understand the sentence you hear." A countdown box to track the progress was located at the bottom right corner of the screen. The listeners rated EOU on a visual analogue scale marked with the endpoints "Difficult" and "Easy." EOU scores range from 0 to 100, with higher scores indicating that speech was easier to understand and lower scores indicating that speech was more difficult to understand. It should be noted that listening effort was not a focus of the experiment, although it could have affected the overall outcomes. Before playing the recordings, the experimenters instructed the listeners to judge the speech based on precision of speech articulation (Tjaden & Wilding, 2004), but avoided prompting the listeners to pay attention to loudness or speech rate.

Prior to completing the experiment, listeners participated in task familiarization. Here they were asked to rate 10 sentences, ranging in length from four to six words, produced by a neurologically healthy female speaker of Mandarin. The sentences in the practice task differed from the test stimuli. All listeners were allowed breaks as needed. The experiment took approximately 50 minutes to complete.

A mean EOU score for each speaker and condition was calculated. Cronbach's alpha was used to measure reliability, yielding a value of above .99 for intra-rater reliability and above .93 for inter-rater reliability.

Acoustic Analysis

Acoustic analysis of the seven experimental stimuli from the Mandarin version of the Rainbow Passage (Fairbanks, 1960) translated by the first author (see Appendix A) in the habitual, loud, and slow conditions was performed by means of Praat software (Boersma & Weenink, 2005). Six measures were included: (1) Vocal intensity in decibels (dB; mean intensity across sentences); (2) duration of pauses in milliseconds (ms), with a pause defined as a silent interval greater than 50 ms (Robb, Maclagan, & Chen, 2004). Criteria for determining pause duration vary across studies, with a convention of an average between 150 and 250 ms. However, silent intervals of 150 ms and above were used because, according to Tosi (1974), silent intervals shorter than 150 ms are associated with articulatory behaviors (e.g., pauses occurring during articulation/speech production), whereas silent intervals of over 250 ms may be more reflective of hesitation pauses (Rochester, 1973); (3) pause frequency (number of pauses within the passage); (4) articulation rate (number of syllables divided by the total speech duration, excluding pauses; see Robb et al., 2004 for details); (5) vowel space, as measured by formant centralization ratio (FCR; Sapir, Ramig, Spielman, & Fox, 2010) using the mean value of the midpoint of the first and second formants (F1 and F2) of /i/, /u/, and /a/ vowels (FCR, expressed as [F2u+F2a+F1u+F1i]/[F2i+F1a]); FCR, rather than the more conventional vowel space area, was selected to measure dysarthric speech in the current study because FCR has been found to be sensitive to vowel centralization, as well as a reliable means of reducing inter-speaker variability. FCR also makes it possible to detect changes in dysarthric speech following treatment (Sapir et al., 2010). Moreover, this measure has been found to correlate with speech intelligibility and vowel accuracy (Lansford & Liss, 2014), and it has been implemented in recent studies on English speakers with hypokinetic dysarthria (Fletcher et al., 2017; McAuliffe et al., 2017); and (6) syllabic F_0 range (differences between the minimum and maximum F_0 across syllables). The selected features have been found to contribute to speech intelligibility in English speakers with hypokinetic dysarthria (e.g., Cannito et al., 2012; Fletcher et al., 2017; McAuliffe et al., 2017; Tjaden & Wilding, 2004) as well as in Mandarin speakers with CP (Jeng et al., 2006; Liu et al., 2000; Liu et al. 2005).

To establish intra-rater reliability of the acoustic findings, twenty percent of the original sentences were randomly selected and re-assessed. Cronbach's alpha revealed a coefficient above .90 across all acoustic features, suggesting excellent internal consistency (George & Mallery, 2003).

Statistical Analysis

To examine the changes of each acoustic feature following loud and slow cues, univariate analyses of the acoustic features were first performed by means of repeated measures analyses of variance (ANOVA) with post hoc Bonferroni adjustment for pairwise comparisons using SPSS 24 (IBM Corp., 2017). A preliminary check was conducted using Shapiro-Wilk normality tests on the acoustic features in each speaking condition. When the normality assumptions were not met ($p < .05$), a nonparametric Kruskal-Wallis H test was performed instead. The significance level was set at $\alpha = .05$.

Multivariate analyses were then conducted to assess the interrelationships between selected acoustic features and EOU in the loud and slow conditions with structural equation modeling (SEM) using Mplus 7.3 (Muthén & Muthén, 1998–2015).

Results

EOU

Figure 1 shows mean listener ratings of EOU for each speaker across the three speaking conditions—habitual ($M = 52.64$, $SD = 18.42$), loud ($M = 72.27$, $SD = 19.12$), and slow ($M = 59.73$, $SD = 23.64$). In the loud condition, mean ratings increased relative to the habitual condition for all speakers, although the gains varied across speakers. All speakers appeared to benefit from the loud condition, at least to some degree. In the slow condition, EOU increased for most speakers, although less so than in the loud condition.

[Insert Figure 1 here.]

There was a significant difference in the mean EOU scores across the speaking conditions, $F(2, 20) = 10.91$, $p = .001$. Post hoc pairwise comparisons revealed that EOU was significantly higher in the loud condition than in the habitual condition ($p < .001$), providing strong evidence of increased EOU when speakers were cued to speak loudly, while EOU was not found to differ between the slow and habitual conditions ($p = .13$), nor between the loud and slow conditions ($p = .30$).

Acoustic Outcomes

Table 2 details the mean, standard deviation, and test statistics of the acoustic outcomes across the habitual, loud, and slow conditions. All acoustic variables except total pause duration and total pause frequency across passages were normally distributed. The results indicate that cues to increase vocal loudness and to reduce articulation rate had differential effects on the selected acoustic features. Three measures with differences in the pairwise comparisons are described below: vocal intensity, articulation rate, and total pause frequency across the passage.

[Insert Table 2 here.]

Vocal intensity. There was a significant difference across the speaking conditions, $F(2, 20) = 11.08$, $p = .001$, with significant post hoc pairwise comparisons only between the loud and habitual ($p = .007$) conditions and between the loud and slow conditions ($p = .01$). In other words, vocal intensity increased significantly when Mandarin speakers with hypokinetic dysarthria were cued to speak loudly.

Articulation rate. A significant difference was found across the conditions, $F(2, 20) = 4.04$, $p = .03$, with marginally significant post hoc pairwise comparisons between the loud and slow conditions ($p = .06$). These results provide limited evidence that Mandarin speakers with hypokinetic dysarthria slowed their speech when cued to speak slowly.

Total Pause frequency. There was a marginally significant[1] difference in pause frequency across the conditions, $\chi^2(2, N = 33) = 5.42$, $p = .067$, with a marginally significant post hoc pairwise comparison between the habitual and slow condition ($p = .095$). Thus, there is limited evidence to suggest that pause frequency increased when Mandarin speakers with hypokinetic dysarthria were cued to speak slowly.

Interrelationships between EOU and Acoustic Features

Next, the contribution of the acoustic features to EOU by modeling the interrelationships between EOU and the acoustic features is examined. Appendix B shows the generic one-factor conceptual model to estimate these interrelationships of interest: It hypothesizes that a number of measured variables (i.e., the *n* indicators) share some hidden trait (i.e., the latent factor), which, in turn, is related to the outcome variable. The variables in squares are measured variables, with their potential errors marked as circled Es. Two SEM analyses separately for the loud and slow conditions were then performed. The two models included four indicators and one outcome variable using the minimum ratio of subjects to variables suggested by Kline (1979). Provided that the outcome variable was normally distributed in the loud and slow conditions ($p > .05$ for both), the SEM models were estimated with maximum likelihood.

SEM model in the loud condition. Table 3 summarizes the correlation between EOU and the acoustic features in the loud condition. The strengths of these correlations suggest that modeling the interrelationships using the linear regression approach was appropriate. Prior to running the SEM analysis, we examined whether a strong correlation existed across the explanatory variables, as this might lead to multicollinearity in regression analysis. As shown in Table 3, in the loud condition, pause duration and pause frequency were strongly associated ($r = .96$, $p < .001$), suggesting that the two variables were redundant and should not be placed in the same model.

[Insert Table 3 here.]

SEM Model 1 (Figure 2) shows the interrelationship between EOU and four acoustic features (intensity, pause duration, FCR, and syllabic F_0 range) in the loud condition. As noted above, pause duration was highly correlated with pause frequency in both loud and slow conditions, indicating that the results based on either variable are identical. The results of the models that include pause duration are reported below.

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[1] Commonly, *p*-values between .05 and .10 are referred to as marginally significant in social sciences studies (Lewis-Beck, Bryman, & Liao, 2004).

[Insert Figure 2.]

Model 1 hypothesized the following: First, the four explanatory variables might share similarities and could be explained by one latent factor, namely "latent trait A." (Latent trait A was defined as the acoustic properties of speech sounds.) Second, "latent trait A" might help explain the variation in the outcome variable, i.e., EOU. The fit indices provided a very good model fit, $\chi^2(5) = 2.37$, ($p > .05$), RMSEA = .00 (90% CI .00–.27), CFI= 1.00, TLI = 1.25, SRMR = .10. The relationship between latent trait A and EOU was positive and statistically significant ($\gamma_{11} = 1.22$, $p < .001$), indicating that EOU increased as the value of latent trait A increased. In addition, two acoustic features were explained by latent trait A: The loading of vocal intensity was positive, strong, and statistically significant ($\lambda_{11} = .60$, $p = .001$), and the loading of FCR was negative, strong, and statistically significant ($\lambda_{31} = -.68$, $p < .001$). In other words, a positive change in latent trait A was associated with increased vocal intensity and decreased vowel centralization. Overall, the findings of Model 1 suggest that in the loud condition, EOU improved as vocal intensity increased and vowel centralization decreased.

SEM model in the slow condition. Table 4 summarizes the correlations between EOU and the acoustic features in the slow condition. The correlation strengths suggest that the regression approach was adequate. The strong correlations between pause duration and articulation rate ($r = -.84$, $p = .001$) and between pause duration and pause frequency ($r = .99$, $p < .001$) indicate that the two variables in each pair are identical and should not be placed in the same model.

[Insert Table 4 here.]

In the slow condition, an SEM model (Model 2) using the same four explanatory variables as seen in Model 1 was fit. As expected, the fit indices again displayed a very good model fit, $\chi^2(5) = 1.72$, $p > .05$, RMSEA = .00 (90% CI .00–.20), CFI = 1.00, TLI = 1.72, SRMR = .09. The relationship between latent trait A and EOU was positive and statistically significant ($\gamma_{11} = 1.36$, $p = .01$). That is, EOU improved as the value of latent trait A increased. In addition, the loading of vocal intensity was positive ($\lambda_{11} = .55$, $p = .05$) and the loading of FCR was negative ($\lambda_{31} = -.46$, $p = .095$), with both being marginally significant. That is, limited evidence was found for a positive change in latent trait A being associated with increased vocal loudness and decreased vowel centralization. Overall, in the slow condition, the results suggested that EOU improved as vocal loudness increased and vowel centralization decreased.

[Insert Figure 3.]

Alternative models. In order to examine articulation rate, two alternative models for the two conditions were fit. For the loud condition (with intensity, articulation rate, FCR, and syllabic F_0 range as the four indicators), the relationship between latent trait A and EOU was positive and statistically significant ($\gamma_{11} = 1.21$ $p < .05$), and the loadings of intensity ($\lambda_{11} = .61$, $p = .001$) and FCR ($\lambda_{13} = -.66$, $p < .001$) were significant. In other words, there is evidence of a positive change in latent trait A associated with increased vocal intensity and decreased vowel centralization.

Similarly, an alternative model for the slow condition (with intensity, articulation rate, FCR, and pause frequency as the four indicators) was fit. The relationship between latent trait A and EOU was positive and statistically significant ($\gamma_{11} = 1.52$, $p < .05$). The loadings of intensity ($\lambda_{14} = .44$, $p = .086$), articulation rate ($\lambda_{14} = .42$, $p = .081$) and FCR ($\lambda_{14} = -.42$, $p = .085$) were marginally significant. That is, there is limited evidence of a positive change in latent trait A being associated with these acoustic features.

Discussion

The current study investigated the effects of cueing for loud and slow speech on speech intelligibility and acoustics of Mandarin speakers with hypokinetic dysarthria due to PD. Cueing for increased loudness and reduced rate yielded differential changes on the speakers' intelligibility and acoustics, with greater gains in ease of understanding brought about by cueing speakers to speak loudly.

Effects of Speech Cues on EOU

Overall, the majority of the speakers exhibited greater EOU gains in the loud condition relative to the habitual and slow conditions. In other words, these speakers' EOU improved when they were cued to speak loudly. These findings are in agreement with results from Cantonese (Whitehill & Wong, 2007), English (McAuliffe, Kerr, Gibson, Anderson, & LaShell, 2014; McAuliffe, Fletcher, Kerr, O'Beirne, & Anderson, 2017; Tjaden, Sussman, & Wilding, 2014), and Spanish (Moya-Galé et al., 2018; Moya-Galé et al., 2016). It should be noted that the stimuli in the above-mentioned studies and the present study differed not only in the languages examined, but also the types of speech samples studied. For example, Moya-Galé et al. (2018) examined conversational speech, whereas the English studies mentioned above and the current study investigated speech produced during reading. Thus, it is possible that cueing for loudness might improve intelligibility in various contexts of speech. There was no statistical evidence to indicate that EOU benefited from the rate reduction strategies. Therefore, cueing for reduced rate might not be as effective as cueing for loudness in Mandarin speakers with hypokinetic dysarthria. It was speculated that there might have been confounding factors, such as severity of dysarthria, that adversely affected EOU outcomes in the slow condition. In the present study, while most speakers seemed to benefit more from loud speech, two speakers (P1 and P3) with more severe dysarthria were rated as having lower EOU in the slow condition relative to the habitual condition. Similarly, in a Dutch study that investigated the effects of rate control on intelligibility, the two speakers (out of 13 speakers), both of whom had severe dysarthria (one due to PD and the other due to a stroke), were rated as having lower intelligibility in a slow condition relative to a habitual condition (Van Nuffelen et al., 2010). It is thus possible that cueing for reduced rate had negative effects on speakers with more severe dysarthria. Another reason for reduced EOU in the slow condition might be related to the concomitant reduction in speech naturalness (Yorkston, Beukelman, Strand, & Hakel, 2010). Slow speech can be perceived as unnatural-sounding (Schiavetti, & Metz, 1996; Yorkston et al., 2010). Thus, given that the Mandarin speakers exhibited a habitually slow speech rate, it is plausible that as rate decreased following the rate reduction cues, their speech became less natural-sounding, resulting in decreased EOU.

Effects of Speech Cues on Vocal Intensity and Global Speech Timing

Cueing for increased loudness and reduced speech rate had differential effects on the selected acoustic features in the current study. As expected, vocal intensity significantly increased in the loud condition, in line with findings from previous speech cues studies in English (Neel, 2009; Tjaden & Wilding, 2004) and LSVT LOUD studies in English (Cannito et al., 2012; Ramig et al., 1995; Sapir et al., 2007; Spielman, Ramig, Mahler, Halpern, & Gavin, 2007). The results are also consistent with Whitehill and Wong (2007), indicating greater vocal intensity in Cantonese speakers with hypokinetic dysarthria following LSVT LOUD. It should be noted that speech samples varied across the studies mentioned here, with single phrases used in Neel et al. (2009) and Sapir et al. (2007) and reading passages used in the other studies (Ramig et al., 1995; Spielman et al., 2007). Still, the average vocal SPL increased 7–9 dB in the loud condition relative to the habitual condition in both English and Mandarin speakers with hypokinetic dysarthria across these studies. Thus, it is likely that treatment targeting increased vocal loudness can effectively increase vocal SPL in speakers with hypokinetic dysarthria across different speech tasks.

Cueing for rate reduction resulted in a trend toward an increased number of pauses in the slow condition relative to the habitual condition, but no differences in pause duration were found between any conditions. It is possible that Mandarin speakers strategically paused more frequently to slow down speech rate rather than prolonging pauses. Additionally, cueing for rate reduction elicited a trend toward slower articulation rate in the slow condition relative to the loud condition, but no articulation rate differences between the habitual and loud or between the habitual and slow conditions were found. These results are not surprising, given that the speakers' articulation rate was already slow in the habitual condition, potentially explaining the lack of statistically significant results. These findings might support our hypothesis that Mandarin speakers with PD paused more frequently to differentiate the (cued) slower speech from their habitually slow speech.

Effects of Speech Cues on Syllabic F_0 Range

Our Mandarin speakers produced changes in F_0 range at the syllabic level in the loud condition. However, these changes were not statistically significant. These results contrast with the findings in studies of English speakers indicating changes in F_0 at the sentence level following cueing for increased vocal loudness (Neel, 2009; Ramig et al., 1994; Tjaden & Wilding, 2011a). However, they are in line with findings from Whitehill and Wong (2007), who showed that Cantonese speakers with hypokinetic dysarthria improved sentence F_0 but not syllabic F_0 following LSVT LOUD. Taken together, the findings from the current and previous studies support Vance's (1976) suggestion that the sentence and syllabic F_0s might be controlled by different physiological mechanisms. Thus, increased vocal loudness may not affect the physiological mechanisms that are responsible for manipulating syllabic F_0 changes.

Similarly, no statistically significant increase in syllabic F_0 range in the slow condition was found. This is consistent with Xu's (1998) findings that cueing for slow rate did not affect syllabic F_0 peak or slope in neurologically healthy speakers of Mandarin. Hence, other factors, such as syllable context, may account for the changes of syllabic F_0. Xu and Xu (2003) found that consonant aspiration produced by neurologically healthy speakers of Mandarin was associated with significant increases in F_0 in the following vowel. Moreover, the F_0 contour of Mandarin tones nested in a Mandarin vowel (Chen et al. 2013), with a high F_0 also had a high F_0 onset (Xu & Xu, 2003). However, as consonant acoustics were not examined in the current study, any relationship between consonant and syllabic F_0 variation could not be ascertained. It should be noted that syllabic F_0 range findings provide information on how the speech cues affected one aspect of syllabic F_0, but other aspects, such as F_0 contour, warrant further examination because the F_0 contour of lexical tones is an important cue for sentence intelligibility in Mandarin (Chen, Wong & Hu, 2014; Patel, Xu & Wu, 2010).

Effects of Speech Cues on Vowel Acoustics

The vowel quadrilaterals of the Mandarin speakers with hypokinetic dysarthria were compressed compared to those of neurologically healthy speakers studied by Chen and Wang (2011). When the speakers in the present study were cued to speak loudly and slowly, their vowel quadrilaterals increased minimally (see Figure 4). Furthermore, no statistical evidence was found that would demonstrate that vowel centralization decreased as a function of the speech cues. In general, these results are in keeping with the findings of Tjaden and Wilding (2004) for English speakers with hypokinetic dysarthria, as well as those of Moya-Galé et al. (2018) for Spanish speakers with hypokinetic dysarthria, in that vowel space was limited in habitual speech and did not expand with increased loudness. Overall, the results do not show benefits of cueing for loudness or rate reduction for vowel space expansion in Mandarin speakers with hypokinetic dysarthria.

[Insert Figure 4 here.]

The Relationship between EOU and Acoustic Features

Among all acoustic features, increased vocal intensity and decreased vowel centralization made the greatest contributions to EOU in the loud condition. It was expected that the speakers' EOU would increase as their vocal intensity increased, in line with the findings from Tjaden and Wilding's (2004) study of English speakers with PD. However, the relationship between decreased vowel centralization and EOU was unexpected, given that the FCR produced by the Mandarin speakers did not decrease significantly in the loud condition. Nevertheless, these results were in partial agreement with Sapir et al.'s (2007) findings of significantly larger vowel space as a result of LSVT LOUD and a significant correlation between larger vowel space and intelligibility in English speakers with PD. Thus, it appears that in Mandarin, which has just nine monophthongs (Whitehill & Ma, 2014) and thus a smaller vowel inventory than English, cueing for increased vocal loudness resulted in increased EOU, but without increasing vowel articulatory excursion.

While there was strong evidence that greater vocal intensity and decreased vowel centralization were associated with higher EOU in the loud condition, there was only limited evidence of such a relationship in the slow condition. It is possible that the lack of strong evidence was partially due to the small sample size. However, the inconsistency may also suggest that vocal intensity and vowel centralization made greater contributions to EOU in the loud condition than in the slow condition. This result also implies that slow speech might not be as effective as loud speech in stimulating laryngeal and articulatory movements in Mandarin speakers with hypokinetic dysarthria.

Conclusion and clinical implications

The current study provides preliminary evidence regarding the utility of common behavioral speech strategies for Mandarin speakers with hypokinetic dysarthria. Cueing for increased vocal loudness, but not reduced speech rate, may increase EOU in this population. These findings are consistent with patterns found in typologically different languages, such as English (Tjaden et al., 2014) and Spanish (Moya-Gale et al., 2018). The effects of speech cues are worth examining across additional languages to ascertain any language-specific versus language-universal benefits of such strategies.

Finally, in the present study, the overall improvements reflected immediate or short-term effects of cueing for increased vocal loudness. The finding that increased intensity and decreased

FCR were associated with increased EOU suggests that treatment targeting increased loudness and vowel accuracy might lead to greater EOU in Mandarin speakers with hypokinetic dysarthria. However, unlike cueing studies, treatment studies investigate longer-term effects, and aim to train new speech habits; thus, such treatment studies are needed on Mandarin-speaking adults with hypokinetic dysarthria. Treatment with a focus on increasing loudness in English speakers with hypokinetic dysarthria has shown short and long-term (12-24 months) improvements in speech function (Ramig et al., 1996; Ramig et al., 2001). Thus, similarly, in Mandarin speakers, phonatory as well as articulatory functions might be expected to improve, along with increased speech intelligibility, following similar intensive speech treatment (Ramig et al., 1995; Ramig et al., 1996).

In contrast, the present study showed limited evidence of the relationship between EOU and speech reduction strategies. Hence, there is less evidence that a treatment centered on decreasing speaking rate would be beneficial to Mandarin speakers with hypokinetic dysarthria. Because the Mandarin speakers with hypokinetic dysarthria in the present study exhibited habitually slow speech, treatment with a focus on pacing at a normal speech rate — which could potentially result in more natural-sounding speech — should be considered. Ultimately, given that communicative participation in PD is likely to be associated with perceived speech disorder (McAuliffe et al., 2016), positive outcomes for communicative participation would be expected following improved speech intelligibility and naturalness in Mandarin-speaking patients with hypokinetic dysarthria.

Limitations and Future Directions

The current study has a number of limitations. Firstly, the use of an EOU rating measure provides a less direct and objective measure of intelligibility than orthographic transcription. Additionally, it provides less information on the particular speech sounds or linguistic units associated with lower EOU. Secondly, the small sample size of Mandarin speakers with hypokinetic dysarthria did not permit an investigation into what extent the severity of dysarthria might affect outcomes. Thus, future investigations with greater numbers of participants could explore the loci of speech errors and effects of dysarthria severity. In addition, acoustical analysis of consonants would further our understanding of the effects of consonants on syllabic F_0 and speech intelligibility. In the current study, F_0 contours or formant slopes at the syllabic level were not addressed. This acoustic feature should be investigated in a future study as it is thought to affect lexical tone and sentence intelligibility (Chen et al., 2014; Patel et al., 2010). However, because Mandarin is a tonal language, future studies should include the effects of loud and slow cues on changes in these tonal acoustics. And finally, given that cueing for loud speech had more immediate effects on increasing EOU as compared to cueing for slow speech, cross-language treatment studies are warranted to assess the long-term retention of speech modifications and their language-specific and/or language-universal impact on intelligibility.

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Table 1. Biographical details of the 11 Mandarin-speaking patients with hypokinetic dysarthria.

Participant	**Age**	**Sex**	**Years post diagnosis**	**Dysarthria severity**
P1	76	M	1	Moderate
P2	62	M	10	Mild
P3	73	F	23	Severe
P4	79	F	14	Moderate-severe
P5	80	M	16	Moderate
P6	75	M	6	Moderate-severe
P7	83	M	5	Mild
P8	79	M	16	Moderate
P9	65	M	8	Moderate
P10	68	F	12	Moderate-severe
P11	68	M	18	Mild

Table 2. Mean values, standard deviation (SD), and F-test statistic for selected acoustic features across the habitual, loud, and slow conditions.

Acoustic features	**Habitual ($M \pm SD$)**	**Loud ($M \pm SD$)**	**Slow ($M \pm SD$)**	$\boldsymbol{F}$	$\boldsymbol{p}$
Vocal intensity (dB)	48.7±4.19	57.39±6.88	50.89±6.39	11.08	.001**
Articulation rate (syll/s)	2.83±0.59	3.03±0.92	2.52±0.75	8.08	.03*
FCR	1.43±0.15	1.35±0.26	1.35±0.28	0.97	.40
Syll F_0 range (Hz)	97.33±52.78	101.78±34.87	119.85±85.47	0.81	.46
	Habitual Mean rank	**Loud Mean rank**	**Slow Mean rank**	χ^2	p
Total pause dur (psg/s)	13.73	15.09	22.18	4.85	.09
Total pause freq across psg	12.91	15.82	22.27	5.42	.067

Note. syll = syllabic, FCR = formant centralization ratio, dur = duration, psg = passage, freq = frequency

$^{**}p < .01$, $^{*}p < .05$

Table 3. Correlation between speech measurements across speakers in the loud condition.

Feature	1	2	3	4	5	6	7
(1) EOU	-						
(2) Vocal intensity	.72**	-					
(3) Total pause dur across psg	-.34	.88**	-				
(4) Total pause freq across psg	-.40	.83**	.96**	-			
(5) Articulation rate	.30	.83**	.57*	-.56*	-		
(6) FCR	-.80**	.26	.33	.40	.10	-	
(7) Syl F_0 range	-.51	.37	.10	.24	-.47	.23	-

Note. EOU=ease-of-understanding, dur=duration, psg=passage, freq=frequency, FCR=formant centralization ratio
$^{**}p < .01$, $^{*}p < .05$

Table 4. Correlation between speech measurements across speakers in the slow condition.

Feature	1	2	3	4	5	6	7
(1) EOU	-						
(2) Vocal intensity	.74**	-					
(3) Total pause dur across psg	-.18	.88**	-				
(4) Total pause freq across psg	-.24	.89**	.99**	-			
(5) Articulation rate	.63*	-.84**	-.51	-.52	-		
(6) FCR	-.62*	.11	-.04	.09	-.09	-	
(7) Syl F_0 range	-.22	.43	.29	.32	-.41	.23	-

Note. EOU=ease-of-understanding, dur=duration, psg=passage, freq=frequency, FCR=formant centralization ratio
**p* < .05, ***p* < .01

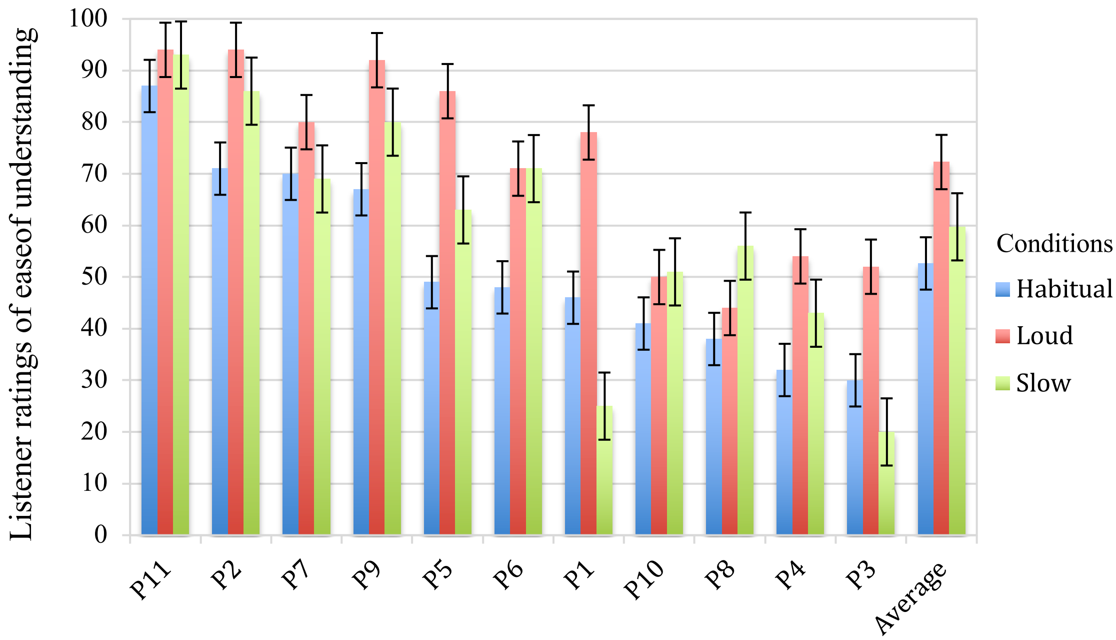


Figure 1: Mean ease-of-understanding (EOU) scores with standard error bars for the 11 speakers with hypokinetic dysarthria across the habitual, loud, and slow conditions.

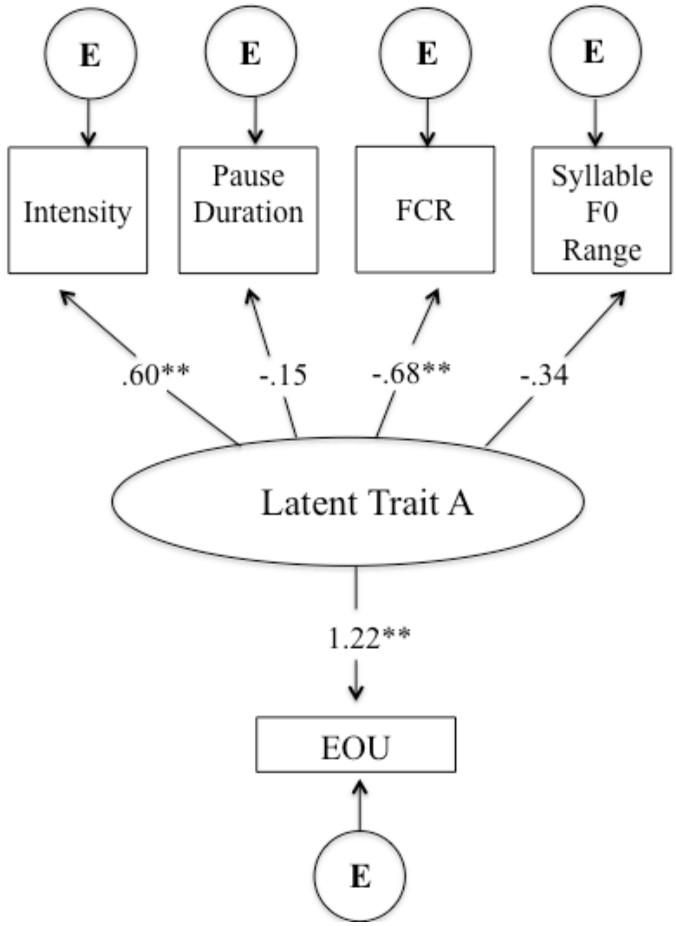


Figure 2. Standardized parameter estimates in the loud condition (Model 1).

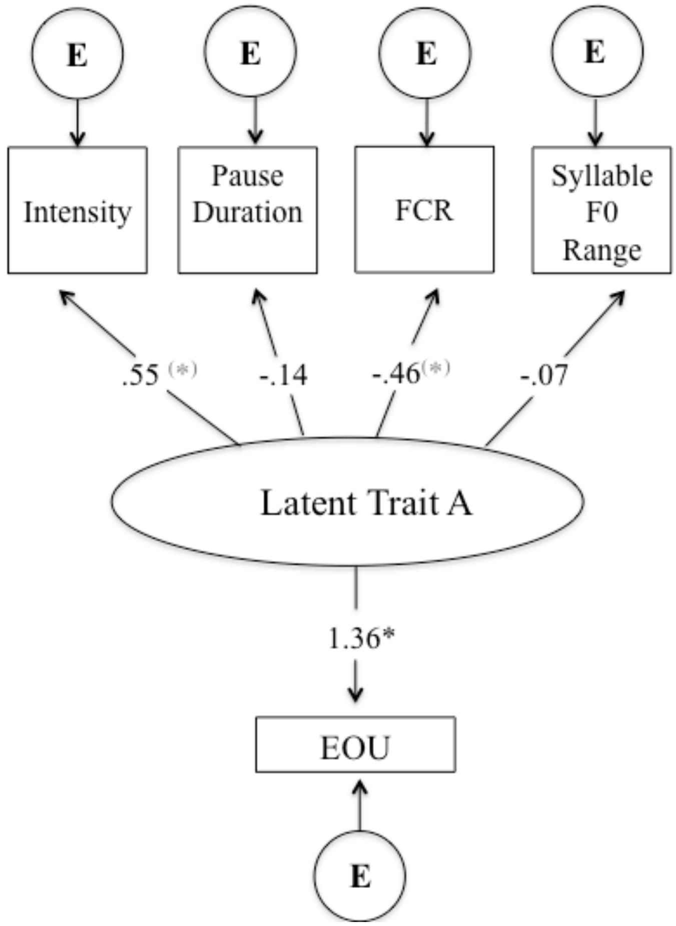
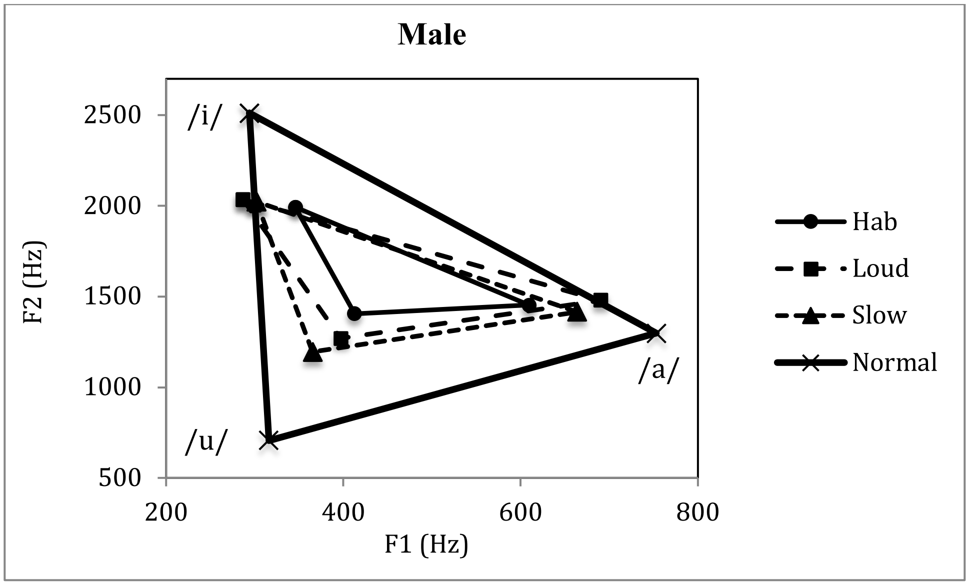


Figure 3. Standardized parameter estimates in the slow condition (Model 2).



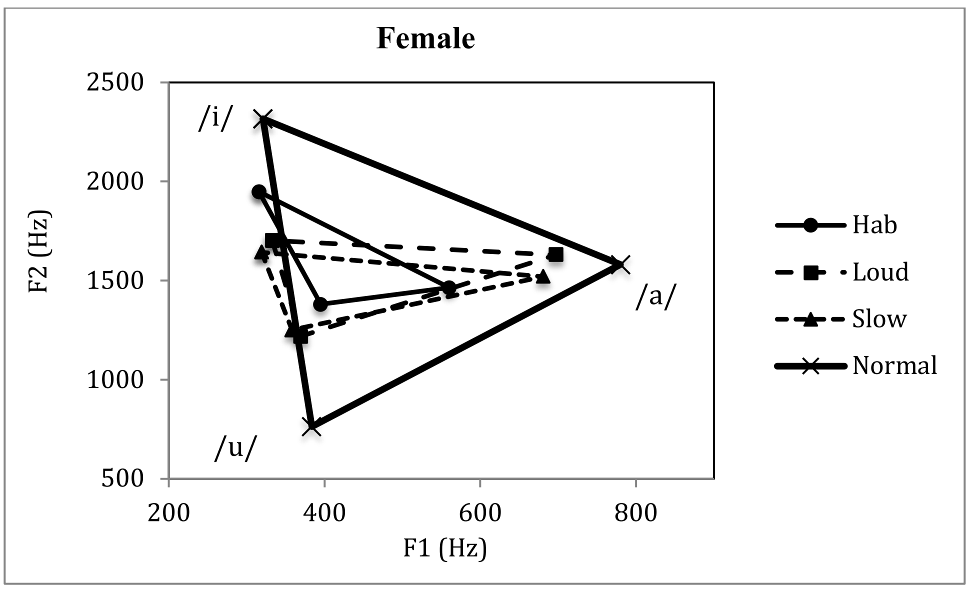


Figure 4. Vowel quadrilaterals in the habitual, loud, and slow conditions for female and male speakers. Normal vowel quadrilaterals were adapted from Chen and Wang (2011).

Appendix A. The Mandarin translation of the Rainbow Passage (Fairbanks, 1960) with sentences numbered, translation by Hsu (first author).

當日光照射到空氣裡的雨滴時，雨滴如同一面菱鏡般將光線折射成彩虹(1)。事實上，彩虹是由七種不同頻率的白光組成(2)。彩虹如同一道長條拱狀物高掛在天空中，兩邊尾巴低於水平線(3)。傳說中彩虹的尾巴藏了滿滿的黃金(4)。人們開始尋找藏在彩虹裡的黃金，但從來沒有人找到(5)。當有人想要做超乎他能力所及的事情時，會譬喻為他在找藏在彩虹裡的黃金(6)。過去幾百年中有不同的方法解釋彩虹形成的原因(7)。有些人認為彩虹是奇蹟(8)。而希伯來人認為彩虹是世界上不再有大洪水的證據(9)。希臘人曾經想像彩虹是天神用來傳達有戰爭或大雨的象徵(10)。諾斯曼人則認為彩虹是天神穿梭家與天空的橋樑(11)。有一群人嘗試用物理的角度來解釋彩虹(12)。亞里斯多德認為彩虹是因為太陽光線經過雨水的折射所形成(13)。雖然彩虹形成的理由眾說紛紜，但物理**學家證**實了彩虹不是倒影，而是經由**陽光照**射在水珠的光線折射所形成(4)。 水珠的大小決定彩虹的形狀，當水珠越大，彩虹每道顏色的間層就越大(15)。確切來說，彩虹顏色是經由虹與虹的堆疊而產生(16)。當紅色的虹落在綠色的虹之上，就會形成一道鮮黃**的**虹(17)。猶如把紅色和綠色混在一起時就會產生黃色(18)。紅色與黃色的虹很常見，但綠色或藍色的虹就較稀少(19)。

Appendix B. Generic conceptual structural equation modeling (SEM).