Research Article

Dysarthria in Mandarin-Speaking Children With Cerebral Palsy: Speech Subsystem Profiles

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Purpose: This study explored the speech characteristics of Mandarin-speaking children with cerebral palsy (CP) and typically developing (TD) children to determine (a) how children in the 2 groups may differ in their speech patterns and (b) the variables correlated with speech intelligibility for words and sentences.
Method: Data from 6 children with CP and a clinical diagnosis of moderate dysarthria were compared with data from 9 TD children using a multiple speech subsystems approach. Acoustic and perceptual variables reflecting 3 speech subsystems (articulatory-phonetic, phonatory, and prosodic), and speech intelligibility, were measured based on speech samples obtained from the Test of Children's Speech Intelligibility in Mandarin (developed in the lab for the purpose of this research).
Results: The CP and TD children differed in several aspects of speech subsystem function. Speech intelligibility scores in children with CP were influenced by all 3 speech subsystems, but articulatory-phonetic variables had the highest correlation with word intelligibility. All 3 subsystems influenced sentence intelligibility.
Conclusion: Children with CP demonstrated deficits in speech intelligibility and articulation compared with TD children. Better speech sound articulation influenced higher word intelligibility, but did not benefit sentence intelligibility.

Cerebral palsy (CP) is a nonprogressive neuromuscular disorder caused by a lesion of the brain that happens before, during, or shortly after an infant's birth. The prevalence of CP is estimated to be between 1.5 and 2.5 per 1,000 live births (Robb, 2010). CP is the most common cause of motor disability in children (Lepage, Noreau, Bernard, & Fougeyrollas, 1998) and usually is accompanied by disturbances of sensation, perception, cognition, behavior, and communication (Bax et al., 2005), which can profoundly affect quality of life (Kennes et al., 2002; Liptak et al., 2001).

In a sample of children with CP in Europe, 58% were found to have some type of communication problems (Bax, Tydeman, & Flodmark, 2006); similar results were reported in a register study by Parkes, Hill, Platt, and Donnelly (2010) and in a population-based study by Nordberg, Miniscalco, Lohmander, and Himmelmann (2013). More recently, dysarthria was reported to affect 90% of children with CP (Mei, Reilly, Reddihough, Mensah, & Morgan, 2014). Historically, the main focus of research related to communication problems has been dysarthria. Several studies (Achilles, 1955; Ansel & Kent, 1992; Platt, Andrews, & Howie, 1980; Platt, Andrews, Young, & Quinn, 1980; Schölderle, Staiger, Lampe, Strecker, & Ziegler, 2016; Wolfe, 1950) have investigated the characteristics of dysarthric speech in adults with CP and revealed disorders affecting several aspects of speech production. There have been fewer studies of speech characteristics in children with CP; however, recent efforts have been made to describe speech and communication abilities in this population (Cockerill et al., 2014; Hustad, Gorton, & Lee, 2010; Novak et al., 2013; Parkes et al., 2010; Pennington et al., 2013).

Although there is not a widely accepted classification system for childhood dysarthria (Lowit & Kent, 2017; van Mourik, Catsman-Berrevoets, Yousef-Bak, & van Dongen, 1997), one of the major approaches taken in both assessment and treatment is to consider functional subsystems that underlie speech production (Lowit & Kent, 2017; Netsell, 1984; Netsell & Daniel, 1979). Examples of subsystems recognized in recent studies of dysarthria in children and/or adults are the following.

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1. Articulatory, resonatory, phonatory, and respiratory (Green et al., 2013; Rong et al., 2016).
2. Articulation, voice quality, nasality, and prosody (De Bodt, Hernández-Díaz Huici, & Van De Heyning, 2002).
3. Articulatory, velopharyngeal, and laryngeal (Lee, Hustad, & Weismer, 2014).
4. Respiration, pitch and loudness, voice quality, voice stability, articulation, resonance, articulation rate, fluency, and modulation (Schölderle et al., 2016).

The number of subsystems and the names given them vary across studies, but the common theme is that speech motor disorders can be understood in terms of a finite number of participating subsystems. These can be evaluated with different methods, including perceptual judgments, physiological recordings, or acoustic analyses. Netsell (1984) pointed out that physiological assessments of motor subsystems have the advantage of offering controlled and systematic observations but that these data are fully interpretable only when their acoustic and perceptual consequences are taken into account. Because the subsystems are interactive, various combinations of compensation and interdependency can vary from one individual to another. Therefore, the results from a subsystem analysis (perceptual, acoustic, or physiologic) are best considered relative to global performance measures such as speech intelligibility or quality. In this way, a deficit in intelligibility or a disorder in quality can be linked to the contributions from the participating motor subsystems.

A subsystem perspective also offers opportunities to study several important issues. For example, it is important to understand the language-universal versus language-specific effects of CP on speech production. Cross-language studies are essential to answering this question, but very few such studies have been published for most communication disorders (Miller & Lowit, 2014; Wong, Perrachione, Gunasekera, & Chandrasekaran, 2009). Particularly needed are data on speakers of tone languages, including Mandarin Chinese, the most widely spoken tone language. In addition, subsystem-based studies enable the characterization of how speech features change with maturation and aging in individuals with CP. Schölderle et al. (2016) reported that in their sample of adults with CP, symptoms relating to voice quality, prosody, and respiration were as prominent as symptoms relating to articulation. They noted that this finding differed from that reported for children with CP, which raises the question: What is the natural progression of the speech disorder in cerebral palsy? Moreover, it is important to understand how interventions targeting a particular subsystem lead to improvements in speech intelligibility or quality. Promising results have been reported in several studies (Kuschmann, Miller, Lowit, & Pennington, 2017; Levy, 2014; Miller et al., 2014; Netsell, 1984; Netsell & Daniel, 1979; Pennington, Miller, Robson, & Steen, 2010).

The main focus of the present study is to describe the speech characteristics of children with CP from a tone language, Mandarin, based on variables reflecting the articulatory-phonetic, phonatory, and prosodic subsystems of speech production. Two research questions were addressed in this study.

1. How do children with dysarthria secondary to CP differ from typically developing (TD) children in characteristics of articulation, phonation, prosody, and intelligibility?
2. Which variables are significantly or highly correlated with speech intelligibility for children in the CP and TD groups? What are the differences between the two groups?

Method

The design of the present study was largely based on the procedure of Lee et al. (2014). Some adjustments were made due to the limited number of participants in this preliminary study, the different phonological structures in English and Mandarin, and expectations of the discriminating features in Mandarin (i.e., tone).

Participants

Speakers

Six children with CP and nine TD children were recruited to participate in this study as speakers. Inclusion criteria were native speakers of Mandarin Chinese and normal hearing ability according to the results of otoacoustic emission testing. Children in the CP group had a medical diagnosis of CP and moderate dysarthria as determined by pediatric physiatrists and an experienced speech-language pathologist. The CP group consisted of six children (four boys and two girls) with an average age of 7 years and 5 months (range = 51–105 months, SD = 20). The TD group consisted of nine TD children (five boys and four girls) with an average age of 5 years and 9 months (range = 62–73 months, SD = 3.28). The demographics of the children with CP are shown in Table 1.

Although, ideally, children in the CP and TD groups would be closer in age, it was difficult to recruit children who were matched for age between the two groups. Since children with CP exhibited considerable individual differences and were expected to have delayed development in speech production (Hustad et al., 2016), younger TD children were considered acceptable as a control group. Originally, there were 10 children in the CP group and 10 children in the TD group. In order to focus the study on the speech characteristics of children with dysarthria, four children with CP who had no apparent dysarthria were excluded. In addition, one child in the TD group had extremely low speech intelligibility, which might have been due to an undiagnosed speech disorder and, therefore, was considered an outlier and excluded from this study. Prior to initiating the study, the institutional review board of National Cheng Kung University Hospital approved the study, and the parents of the participants signed a written informed consent form.

Table 1. Demographics of the Mandarin-speaking children with cerebral palsy (CP).

Child	Gender	Age (Year/Month/Day)	Corrected age (Months)	CP diagnosis	GMFCS
CP1	M	7/7/19	91.6	Mixed type (spastic & athetoid)	Level II
CP2	F	4/3/20	51.7	Spastic diplegic	Level III
CP3	M	7/2/01	86.0	Right spastic hemiplegic	Level II
CP4	F	8/9/14	105.5	Spastic diplegic, dyslalia	Level II
CP5	M	6/8/14	80.5	Spastic diplegic	Level IV
CP6	M	8/9/19	105.6	Left spastic triplegic	Level III

Note. M = male; F = female; GMFCS = Gross Motor Function Classification System.

Listeners for Judging Speech Intelligibility

Speech intelligibility judgments were conducted following the procedure of the Test of Children's Speech Plus Word and Sentence Intelligibility Software (TOCS+; Hodge, Daniels, & Gotzke, 2009). Forty-three native speakers of Mandarin were invited to act as listeners; ages were between 18 and 25 years and all had normal hearing. Listeners were not involved in making the recordings, and they had not received any formal training in phonetic transcription. Each listener judged only the utterances in one of two repetition tasks (either words or sentences) from a given child, in order to prevent familiarity with that child's voice and articulation traits. Nevertheless, a listener was allowed to hear the sound file from two to three different children, since the speech stimuli for each child were automatically chosen by the system and varied with individuals. In addition, to ensure the reliability of results, for each child, the recordings of the word repetition task were judged by three different listeners, and the recordings of the sentence repetition task were judged by another three different listeners. Consequently, the recordings of each child's speech were judged by six listeners. The target sentences or words were played to the listeners no more than twice. Listeners were able to adjust the loudness of the speech signal to ensure satisfactory judgment. In addition, listeners evaluated their intelligibility judgments as very certain, certain, or uncertain after hearing recordings of each word or sentence produced by the child speaker. More than 80% of the judgments were reported by the listeners to be very certain or certain. No time constraints were imposed on the judging sessions.

Materials and Recording Procedures

The Test of Children's Speech Intelligibility in Mandarin (TCSIM; developed in the lab for the purpose of this research) was adapted from the TOCS+ (Hodge et al., 2009). Speech samples of children with CP and TD children were obtained from word and sentence repetition tasks.

Words in Mandarin were monosyllabic and were structured as vowel (V), vowel–nasal ending (VC), consonant–vowel (CV), and consonant–vowel–nasal ending (CVC). Only CV and CVC were included in the stimuli. In the word repetition task, 21 consonants /p, pʰ, m, f, t, tʰ, n, l, k, kʰ, x, tɕ, tɕʰ, ɕ, tʂ, tʂʰ, ʂ, ʐ, ts, tsʰ, s/ were respectively combined with front vowels and back vowels to form the target syllables according to the phonotactic rules of Mandarin. Both front and back vowels included single vowels, diphthongs, triphthongs, and vowels with a nasal ending. Theoretically, there should have been 42 sets of consonant–vowel combinations in the wordlist. However, since the combinations of consonants /tɕ, tɕʰ, ɕ/ and back vowels do not occur in Mandarin, only 39 sets of consonant–vowel combinations were considered. Furthermore, the target syllables were combined with tones to form meaningful words. There are four contrastive tones in Mandarin: tone 1 (high level), tone 2 (high rising), tone 3 (low falling–rising), and tone 4 (high falling). To make it more natural for children to understand and follow, the stimuli were designed based on the following criteria: (a) frequently used in daily conversations for young children, (b) could be concretely illustrated by pictures, and (c) in the form of word combinations. For each stimulus, the target word (syllable) was located in the initial position and followed by supplementary words (syllables). Thus, there might be 1–4 words (syllables) in each stimulus (e.g., /ʐo4/ 'meat'; /me3.li4/ 'beautiful'; /kaʊ1.kən1.ɕɪɛ2/ 'high heels'; /tʂu4.ɪn1.fu2.xaʊ4/ 'Mandarin phonetic symbols'; the numbers represent tone categories). All of the syllables in word combinations were included for phonetic transcription and measurements. Since speech data were intended for a longitudinal examination, the words tested were chosen randomly and automatically by the system to avoid familiarity with the stimuli. Therefore, the stimuli selected for each child were different, and the total number of syllables in word combinations initiated with 39 sets of consonant–vowel varied across individuals.

Materials for the sentence repetition task of the TCSIM were developed based on the arrangement of sentence structures in the TOCS+ (Hodge et al., 2009). To adapt to the language ability of children at different ages, the sentences were designed with varied lengths (3–8 syllables) and structures (simple sentences and compound sentences). Moreover, according to children's mean length of utterances, the total syllables of the sentence stimuli were set at 80 syllables for children with CP and 160 syllables for TD children beforehand, regardless of their age. Due to the fixed number of total syllables, the number and length of sentences varied with different age levels. The number and length of sentences were determined by the examiner according to each child's age or language ability when making the recordings. For children from the CP group, the stimuli displayed to CP2 and CP3 were determined based on their age. Since CP1, CP4, and CP5 encountered difficulties repeating the sentences for their corresponding age level, the stimuli for these three children were chosen from an easier level, age 3. However, the stimuli selected for children from the TD group were determined based on their age. Only TD3 and TD4 were tested with a higher level, age 6, according to their language ability.

Recordings were made in a quiet room in the hospital (for children with CP) or in the school setting (for TD children). Auditory presentation of a word or a sentence was given simultaneously with a relevant picture using a laptop at a fixed listening level. Participants were asked to listen to the word or sentence carefully and repeat what they heard after a short “beep” sound. Following this warning sound, each word or sentence was automatically saved as an individual sound file. If the children were unable to follow the directions, they were asked to repeat the stimulus again. Children’s repetitions were recorded by MOTU Audio Express (UltraLite-mk3 Hybrid) and Steinberg Cubase 5 connected to a unidirectional shotgun handheld microphone RØDE NTG3, which enhanced the sound in the forward direction and rejected the background noise. Audio samples were recorded at a sampling rate of 48 kHz and a bit depth of 16 bits. Because some of the children in the CP group were unable to sit still and keep a constant mic-to-mouth distance while making the recording, an assistant held and adjusted the microphone at approximately 5 cm from the child’s mouth. Recording sessions were completed within an hour with some short breaks.

Data Analysis

Acoustic and perceptual measures, percent intelligibility, and speech rate were determined (see Appendix A). Speech intelligibility was computed separately for words and sentences. Acoustic measures, phonetic accuracy rates, and word intelligibility scores for children in the CP and TD groups were obtained from word utterances from the TCSIM. Sentence intelligibility and speech rate measures were based on speech samples of sentences from the TCSIM. However, word productions with significant background noise or poor recording quality were excluded from acoustic and perceptual analyses. Therefore, the number of usable syllables of word productions for variable measurements was different from that for word intelligibility judgments. As to sentences, because of technical problems, words in the initial or final position of some sentences were truncated in some of the TD children. The fragmented sentences accounted for about 18% of the total sentences. In order to report representative results, the fragmented sentences were still included for sentence intelligibility judgment, and only meaningful portions in the sentences were retained for judgment. Nevertheless, the fragmented sentences were excluded from the calculation of speech rate since it was difficult to determine the exact start and end times for the remaining meaningful portions of the sentences. As can be seen in Appendix A, this resulted in different numbers of sentences and total syllables for sentence intelligibility judgment and speech rate. On the other hand, children with CP were allowed to follow the oral prompts of the assistant if they were unable to catch up with the directions, and thus, all sentences produced by children with CP were included for determining sentence intelligibility and speech rate.

CP can affect all subsystems of speech production. Therefore, it was important to examine multiple speech subsystems to characterize the differences between CP and TD groups and identify significant contributing factors to perceptual features of speech. The measures used in this study were selected based on the articulatory-phonetic, phonatory, and prosodic subsystems according to the following three major criteria: (a) a high likelihood of application to the speech of children with CP, (b) relevance to the speech subsystems approach, and (c) suitability to the speech sample. Additional acoustic measures of consonant production were considered, but it was decided not to attempt a large set of such measures for this initial analysis, especially because of methodological challenges associated with variable patterns of consonant production. For example, measures of fricative spectra presuppose the presence of turbulence noise, but fricatives are often omitted in the speech of young children with CP. When fricatives are produced, they may have time-variant spectral content. One goal of the analyses reported here is to provide guidance for a more detailed examination of consonant production in the future.

Articulatory-Phonetic Subsystem

This subsystem is represented by several acoustic measures of vowel production along with perceptual accuracy of vowels, consonants, and tones. Tonal accuracy is included in the articulatory-phonetic subsystem as tones play the same role as consonants and vowels in distinguishing syllable meaning in Mandarin.

Acoustic measures. Vowel formants were estimated from a broadband spectrogram, fast Fourier transform, and linear predictive coding with the TF32 software (Milenkovic, 2005). Formant frequencies of the first two formants (F1 and F2) of the three corner vowels in Mandarin, /i, a, u/, were used to derive four indices of vowel articulation: vowel space area (VSA; Higgins & Hodge, 2002; Liu, Tsao, & Kuhl, 2005), ratio between the F2 values of vowels /u/ and /i/ (F2i/F2u ratio; Moura et al., 2008), formant centralization ratio (FCR; Sapir, Ramig, Spielman, & Fox, 2010), and vowel articulation index (VAI; Roy, Nissen, Dromey, & Sapir, 2009). A total of 243 vowel tokens were included in the calculation. The formulas were expressed as follows:

$$\begin{aligned} \mathrm{VSA} &= \mathrm{ABS}\,((\mathrm{F1/i/} \times (\mathrm{F2/a/} - \mathrm{F2/u/}) + \mathrm{F1/a/} \\ &\quad \times (\mathrm{F2/u/} - \mathrm{F2/i/}) + \mathrm{F1/u/} \times (\mathrm{F2/i/} - \mathrm{F2/a/}))/2) \\ \mathrm{F2u/F2i\ \ ratio} &= \mathrm{F2\ of\ vowel/u//F2\ of\ vowel/i/} \\ \mathrm{FCR} &= (\mathrm{F2/u/} + \mathrm{F2/a/} + \mathrm{F1/i/} + \mathrm{F1/u/})/(\mathrm{F2/i/} + \mathrm{F1/a/}) \\ \mathrm{VAI} &= (\mathrm{F2/i/} + \mathrm{F1/a/})/(\mathrm{F2/u/} + \mathrm{F2/a/} + \mathrm{F1/i/} + \mathrm{F1/u/}). \end{aligned} \tag{1}$$

These four indices were used in combination because of questions raised about the suitability and sensitivity of acoustic measures of vowel articulation (Fougeron & Audibert, 2011; Roy et al., 2009; Sapir, Połczyńska, & Tobin, 2009; Sapir et al., 2010).

Given that previous studies have reported a strong correlation between F2 slope and speech intelligibility (Lee et al., 2014; Weismer, Jeng, Laures, Kent, & Kent, 2001), F2 slope was also measured in the present study. The vowels /aɪ/, /ɪa/, /ɪaʊ/, and /ɪo/ in Mandarin were chosen because they involved changes in terms of vowel frontness and, thus, resulted in differences in the F2 frequency during the vowel transition period. For /aɪ/, the F2 transition between the main vowel and the off-glide part is rising, whereas the F2 transition between the on-glide part and the main vowel for /ɪa, ɪo/ is falling. The triphthong /ɪaʊ/ was also included, but only the F2 transition of /ɪa/ was considered. Therefore, the F2 slopes of /ɪa/ and /ɪaʊ/ were combined and calculated as a group. Following Weismer and Berry (2003), the 20 Hz/20 ms rule was used to determine the onset and offset of the major transition of F2 changes. In total, there were 398 tokens measured. The absolute values of slopes for the three vowels were computed and analyzed separately.

Phonetic accuracy rates. Children's utterances were transcribed using the International Phonetic Alphabet, and the transcriptions were used to calculate the accuracy rates of vowels, consonants, and tones. For vowels, the accuracy analysis was done in all vowels, single vowels, diphthongs, and the most frequently occurring vowels (i.e., /i, ɨ, ə, a, aʊ, ʊa, u/). For consonants, the accuracy rate was computed in terms of major consonant categories according to place and manner of articulation, and the most frequently occurring consonants (i.e., /p, pʰ, m, t, tʰ, l, x, ts/). For tones, the accuracy rate of all tones and individual tones was determined. Five major tones were examined in the current study: high level tone (tone 1), high rising tone (tone 2), low falling–rising tone (tone 3), high falling tone (tone 4), and neutral tone. Native Mandarin speakers usually pronounce low falling–rising tone (tone 3) as a low falling tone. That is, only the falling part is maintained for tone 3. This phenomenon is described as a type of tone sandhi in Mandarin (Chen, 2000, p. 21; Zhang & Lai, 2010, p. 162). Therefore, tone 3 here referred to both low falling–rising tone and low falling tone.

Phonatory Subsystem

This subsystem includes vowel duration, signal-to-noise ratio (SNR), frequency perturbation (jitter), and amplitude perturbation (shimmer), which are associated mostly with the vibratory pattern of the vocal folds (i.e., respiratory–laryngeal features). All measures were estimated automatically by the Praat software program (Boersma & Weenink, 2016).

The beginning and the end of all vowels (i.e., single vowels, diphthongs, triphthongs, and vowels with nasal endings) were identified and annotated using Praat by referring to the first and final uprising zero-crossing in the waveform with reference to the spectrographic display. A total of 478 single vowels were included for measurements of vowel duration (range for CP = 97–706 ms; range for TD = 163–1029 ms). SNR, jitter, and shimmer were estimated using all vowels, including 478 single vowels (monophthongs), 235 diphthongs, 32 triphthongs, and 277 vowels with nasal endings (duration range for CP = 68–644 ms; duration range for TD = 83–1029 ms).

Prosodic Subsystem

The variables measured for this subsystem are speech rate, fundamental frequency (F0), and pitch slope.

Using sentence productions, speech rate was calculated by dividing the number of all syllables by the total duration of the utterance in seconds. Moreover, to avoid the bias of more intelligible syllables in TD children, speech rate based on intelligible syllables was also calculated. The speech rate of intelligible syllables for each child was the mean value of the three listeners. F0 and pitch slope were measured by referring to the same intervals as used for estimating SNR, jitter, and shimmer. Tonal contrast is an important feature in Mandarin that serves to differentiate meaning at the syllable level and is expected to have a close connection with speech intelligibility. Thus, the mean F0 of all tones and individual tones was considered. For pitch slope, only the slopes of tone 2 (high rising) and tone 4 (high falling) were of interest, because these two types of tones have more distinctive contours than the others. The formula for slope was: (maximum F0 − minimum F0)/interval between maximum F0 and minimum F0. Measurements included a total of 344 tokens (98 for tone 2 and 246 for tone 4).

Speech Intelligibility

Speech samples were played to listeners through Superlux HD-681 headphones using TCSIM software. Listeners were instructed to try their best to identify the children's words or sentences and type what they heard into the computer. Speech intelligibility scores were computed by dividing the number of correctly identified syllables by the number of total syllables and multiplying by 100. Three listeners judged the utterances of each child, and a mean intelligibility score was calculated for each child.

Reliability

Interjudge reliability was determined by having a second judge retranscribe 10% of the speech data for phonetic transcription, vowel formant frequency, and vowel duration. For phonetic transcription, the agreement rate between the two transcribers was obtained by dividing the consistent tokens by all retranscribed tokens and multiplying by 100. Interjudge reliability for frequently occurring vowels, frequently occurring consonants, and tones were 97.62%, 88.89%, and 88.3%, respectively, which suggests that the two transcribers had a high level of agreement. Pearson correlations of interjudge reliability for vowel formant frequency were: $r = .74$ for F1 and $r = .92$ for F2 ($p < .01$). For vowel duration, single vowels ($r = .92$) and all vowels ($r = .94$) were also significantly correlated ($p < .01$). These indicated a good interjudge reliability.

Statistical Analysis

Independent-samples t tests were used to compare the differences between children with CP and TD children. Because this study was exploratory and the sample size was very small, it was not possible to use multiple regression analyses to identify predictors of speech intelligibility. As a general rule of thumb, there should be at least 10 participants for every independent variable in a multiple regression analysis (Harris, 1985; Wampold & Freund, 1987). Instead, two-tailed Pearson product–moment correlation analyses were used to explore the relationship between speech intelligibility and each variable for children from both the CP and TD groups. Furthermore, the Pearson correlation analyses were performed on all pairwise combinations of variables to examine intercorrelations.

Results

Comparisons of Speech Variables for Children With CP and TD Children

Speech Intelligibility

Speech intelligibility of the CP and TD groups was compared using an independent-samples t test (see Table 2). Results showed that children with CP had significantly lower speech intelligibility than TD children: sentence, $t(4.22) = -2.83$, $p = .04$, $d = 1.77$; word, $t(13) = -3.03$, $p = .01$, $d = 1.44$. The mean sentence intelligibility was consistently higher than word intelligibility in both groups. Moreover, the standard deviation for sentence and word intelligibility of children in the CP group (SD = 10.92 and 21.28, respectively) was higher than that in the TD group (SD = 2.39 and 6.70, respectively), indicating larger variations in children with CP.

Measures from articulatory-phonetic, phonatory, and prosodic subsystems in the CP and TD groups were analyzed by an independent-samples t test (see Tables 3–5). In addition to the statistical results, observations from descriptive data are also reported because it was difficult to detect significant group differences based on the small sample size (n = 6 for children with CP and n = 9 for TD children) in this preliminary study.

Articulatory-Phonetic Subsystem

Measures for the articulatory-phonetic subsystem included VSA, F2i/F2u ratio, FCR, VAI, F2 slope, and accuracy rates of all vowels, single vowels, diphthongs, frequently occurring vowels, categorized consonants, frequently occurring consonants, all tones, and individual tones. Statistical results are shown in Table 3. TD children had significantly larger VSA, F2i/F2u ratio, and VAI as compared to children with CP, and children with CP had significantly higher FCR than TD children, indicating vowel centralization in children with CP. Effect sizes for the significant group effects, estimated by Cohen's d, ranged from 1.37 for the FCR to 1.72 for the F2i/F2u ratio. In addition, the triangular VSA seemed to be more compressed in the F2 dimension in children with CP compared to children in the TD group (see Figure 1). When comparing the mean frequency values of /i/, /a/, and /u/ for the two groups, children with CP demonstrated significantly lower mean F2 frequency of /i/ and a narrower range of F2 values of

Table 2. Number of word productions and sentences for speech intelligibility judgments and intelligibility scores of Mandarin-speaking children with cerebral palsy (CP) and typically developing (TD) children.

Child	Syllables of word productions	Word intelligibility score (%)	Number of sentences (total syllables)	Sentence intelligibility score (%)
CP1	79	79.75	23 (80)	90.42
CP2	79	66.67	20 (80)	68.33
CP3	82	78.46	14 (80)	95.42
CP4	81	69.55	23 (80)	86.67
CP5	79	75.95	23 (80)	76.67
CP6	81	23.46	—	—
M (*SD*)		65.64 (21.28)		83.50 (10.92)
TD1	68	82.84	36 (160)	100.00
TD2	84	96.03	32 (160)	98.75
TD3	79	94.51	32 (160)	93.33
TD4	55	88.48	32 (160)	98.33
TD5	69	85.51	36 (160)	94.38
TD6	82	95.53	36 (160)	98.54
TD7	58	75.29	36 (160)	96.04
TD8	81	87.65	36 (160)	100.00
TD9	75	89.33	36 (160)	98.33
M (*SD*)		88.35 (6.70)		97.52 (2.39)
t		–3.03*		–2.83*
p		.01		.04
d		1.44		1.77

Note. Em dashes indicate no data, as CP6 was unable to perform the sentence repetition task.
$^*p < .05$.

Table 3. Comparison of means for articulatory-phonetic subsystem measures of Mandarin-speaking children with cerebral palsy (CP) and typically developing (TD) children.

Variable	CP	TD			
	M (*SD*)	*M* (*SD*)	*t*	*p*	*d*
Vowels					
VSA (Hz²)	350803 (122264)	536624 (106463)	−3.13*	.01	1.62
F2i/F2u ratio (Hz)	1.80 (0.27)	2.29 (0.30)	−3.23*	.01	1.72
FCR (Hz)	1.18 (0.15)	1.02 (0.07)	2.45*	.05	1.37
VAI (Hz)	0.86 (0.10)	0.98 (0.06)	−3.04*	.01	1.46
F2 slope /aɪ/	4.18 (3.96)	3.31 (1.35)	0.61	.55	
F2 slope /ɪa/	4.86 (1.60)	5.66 (1.61)	−0.94	.37	
F2 slope /ɪo/	5.93 (2.16)	5.73 (4.11)	0.11	.92	
Accuracy of all vowels (%)	68.97 (12.51)	81.70 (6.33)	−2.62*	.02	1.28
Accuracy of single vowels (%)	84.48 (7.37)	93.11 (5.70)	−2.56*	.02	1.31
Accuracy of diphthongs (%)	79.27 (11.36)	81.91 (11.50)	−0.44	.67	
Accuracy of frequently occurring vowels (%)					
/i/	94.44 (8.61)	100.00 (0.00)	−1.58	.18	
/u/	100.00 (0.00)	100.00 (0.00)			
/a/	88.89 (27.22)	98.41 (4.76)	−0.85	.43	
/ə/	90.00 (8.94)	98.41 (4.76)	−2.39*	.03	1.17
/ɨ/	86.90 (11.14)	100.00 (0.00)	−2.88*	.04	—
/aʊ/	74.40 (37.69)	93.78 (9.74)	−1.50	.16	
/ʊa/	86.11 (22.15)	93.75 (17.68)	−0.72	.49	
Accuracy of categorized consonants (%)					
Stop	75.13 (13.39)	88.83 (8.49)	−2.44*	.03	1.22
Nasal	73.17 (17.62)	94.14 (11.15)	−2.84*	.01	1.42
Fricative	48.68 (29.87)	74.01 (19.17)	−2.01	.07	
Affricate	53.03 (22.64)	75.94 (15.52)	−2.34*	.04	1.18
Lateral	63.89 (28.92)	88.89 (18.16)	−2.07	.06	
Labial	77.24 (21.37)	84.06 (12.81)	−0.78	.45	
Alveolar	54.46 (19.29)	78.94 (12.82)	−2.97*	.01	1.49
Velar	74.88 (25.60)	92.34 (11.54)	−1.57	.17	
Accuracy of frequently occurring consonants (%)					
/p/	83.61 (18.57)	83.33 (20.41)	0.03	.98	
/pʰ/	80.56 (22.15)	78.70 (23.24)	0.15	.88	
/m/	80.56 (26.18)	94.07 (12.22)	−1.36	.20	
/t/	75.00 (20.41)	96.30 (11.11)	−2.34	.05	
/tʰ/	60.00 (35.78)	97.22 (8.33)	−2.50	.05	
/l/	63.89 (28.92)	88.89 (18.16)	−2.07	.06	
/x/	81.11 (32.77)	97.78 (6.67)	−1.23	.27	
/ts/	63.33 (36.70)	79.90 (15.34)	−1.16	.27	
Accuracy of all tones (%)	90.87 (6.71)	96.39 (3.47)	−2.11	.06	
Accuracy of individual tones (%)					
Tone 1	95.38 (5.82)	100.00 (0.00)	−1.94	.11	
Tone 2	79.70 (15.42)	95.04 (7.15)	−2.28	.06	
Tone 3	90.26 (14.44)	91.91 (13.60)	−0.23	.83	
Tone 4	91.87 (8.65)	98.83 (2.32)	−1.92	.11	
Neutral tone	94.82 (8.51)	88.52 (15.91)	0.88	.39	

Note. Em dash indicates the value cannot be generated, as the standard deviation for calculating Cohen's *d* should not be zero. VSA = vowel space area; FCR = formant centralization ratio; VAI = vowel articulation index.

*$p < .05$.

the front–back contrast (/i/-/u/) than TD children; however, there was no significant difference with regard to the range of F1 values of the high–low contrast (/i/-/a/). Hence, it was plausible that the limited tongue movements of children with CP were associated primarily with the anterior–posterior dimension.

Among all acoustic measures in the articulatory-phonetic subsystem, only F2 slope was not significantly different between the two groups. Descriptive data for the mean F2 slope of /ɪa/, which accounted for the largest proportion (46.73%) of all tokens used for F2 slope measurement, suggested that children with CP showed shallower F2 slope as compared to TD children. This was in accordance with the previous finding of shallower F2 slopes of dysarthric speakers as compared with normal speakers (Lee et al., 2014, child speakers; Weismer, Yunusova, & Bunton, 2012, adult speakers). However, when comparing the F2 slopes of /aɪ/ and /ɪo/, which respectively accounted for 30.9% and 22.36% of all tokens for measurement, children with CP demonstrated steeper F2 slopes than TD children. This might reflect a bias due to the small sample size and the lesser frequency of occurrence in these two vowels.

Table 4. Comparison of means for the phonatory subsystem measures of Mandarin-speaking children with cerebral palsy (CP) and typically developing (TD) children.

	CP	TD			
Variable	*M* (*SD*)	*M* (*SD*)	*t*	*p*	*d*
Vowel duration (ms)	315.26 (41.74)	368.07 (52.44)	−2.06	.06	
SNR (dB)	11.69 (5.74)	13.00 (3.61)	−0.55	.60	
Jitter (%)	1.97 (0.76)	1.17 (0.33)	2.44*	.05	1.37
Shimmer (%)	11.94 (5.08)	9.26 (3.21)	1.26	.23	

Note. SNR = signal-to-noise ratio.
*$p < .05$.

In perceptual measures, the following were significantly higher in TD children: the accuracy rates of all vowels, single vowels, frequently occurring vowels /ə/ and /ɨ/, categorized consonants, stops, nasals, affricates, and alveolars. Effect sizes for the significant group effects ranged from 1.17 (the accuracy of /ə/) to 1.49 (the accuracy of alveolars). These findings matched general expectations in accounting for reduced intelligibility in children with CP. However, no significant differences were seen with respect to the accuracy rates of diphthongs, other frequently occurring vowels (i.e., /i, u, a, aʊ, ʊa/), other categorized consonants (i.e., fricatives, laterals, labials, velars), frequently occurring consonants (i.e., /p, p^h, m, t, t^h, l, x, ts/), all tones, and individual tones.

Phonatory Subsystem

Measures in the phonatory subsystem contained vowel duration, SNR, jitter, and shimmer (see Table 4). As expected, jitter was significantly lower in TD children, $t(6.28) = 2.44$, $p < .05$, $d = 1.37$. A lower jitter value indicated a more regular pattern in the length of pitch period of the voice signal and was therefore seen as a reference to better voice quality. A lower shimmer value indicated smaller variation in amplitude, whereas a higher SNR indicated higher signal power than the noise power. However, no significant group differences were detected in these two measures. This might be due to the small number of participants in the current study. Descriptive data suggest that TD children exhibited a lower shimmer and a higher SNR compared to children with CP. These findings suggested that group contrasts in terms of voice quality existed and that jitter was likely to be more sensitive in differentiating a pathologic voice from a typical voice.

No significant group differences were observed in vowel duration. However, descriptive data suggest that children with CP exhibited lower mean values of vowel duration than TD children, which differed from the previous findings of Jeng, Weismer, and Kent (2006), Lee et al. (2014), and Patel (2003). Although the children recruited for this study had moderate CP, no obvious prolongations or pauses were detected between words. One explanation might be related to the poor respiratory support of children with CP. In order to repeat the word stimulus in a limited breath group, children with CP tended to go through the whole word rapidly and thus shorten the duration of vowels. Conversely, without the constraint of shallow breathing, TD children were capable of synchronizing the speaking rate of stimulus items when conducting the repetition task, which therefore led to longer vowel duration.

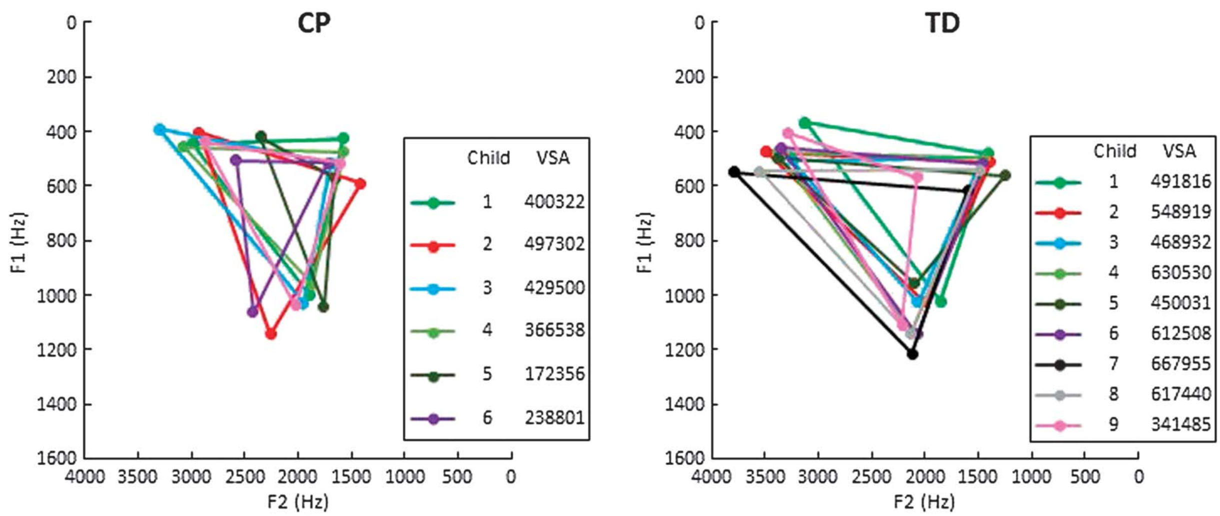
Prosodic Subsystem

Table 5 shows the group means and standard deviations for the prosodic subsystem. Measures comprised speech rate (based on all syllables and intelligible syllables),

Table 5. Comparison of means for the prosodic subsystem measures of Mandarin-speaking children with cerebral palsy (CP) and typically developing (TD) children.

	CP	TD		
Variable	*M* (*SD*)	*M* (*SD*)	*t*	*p*
Speech rate (all syllables/sec)	2.53 (0.53)	2.14 (0.12)	1.65	.17
Speech rate (intelligible syllables/sec)	2.05 (0.27)	2.12 (0.12)	−0.53	.62
F0 of all tones (Hz)	264.23 (44.63)	253.93 (32.27)	0.52	.61
F0 of tone 1	278.24 (55.06)	269.82 (45.36)	0.32	.75
F0 of tone 2	260.18 (46.34)	238.54 (29.51)	1.11	.29
F0 of tone 3	243.52 (42.70)	224.92 (24.39)	0.97	.37
F0 of tone 4	277.10 (44.52)	272.66 (39.95)	0.20	.84
Pitch slope (Hz/ms)				
Slope of tone 2	0.24 (0.09)	0.20 (0.07)	0.95	.36
Slope of tone 4	0.36 (0.13)	0.38 (0.11)	−0.18	.86

Figure 1. Triangular vowel space area (VSA, Hz^2) with corner vowels, /i, a, u/, for Mandarin-speaking children with cerebral palsy (CP, left) and typically developing children (TD, right).



F0 of all tones, F0 of individual tones, and slopes of tone 2 and tone 4. Comparison of the two groups with independent-samples *t* tests failed to detect significant differences between the CP and TD groups. Nevertheless, descriptive findings comparing the mean values of the two groups suggest that children in the CP group had a lower mean speech rate in intelligible syllables. Moreover, consistent with the finding of a shorter vowel duration in the current study, children with CP exhibited a faster speech rate than TD children when it was calculated based on all syllables. This result was contrary to the findings of previous studies (Le Dorze, Ouellet, & Ryalls, 1994; Weismer, Laures, Jeng, Kent, & Kent, 2000). It was assumed that this phenomenon was associated with the poor respiratory support and the limited breath control of children with CP in this study.

Appendix B shows the sentence length and the speech rate of children with CP and TD children. In the CP group, only CP3 was tested with long-sentence stimuli (i.e., the sentence contained over five syllables), but the speech rate of all syllables in CP3 ranked third place. There was no increase in speech rate with longer sentences, which was contrary to general expectations.

In addition, descriptive data of mean F0 showed that children with CP had higher F0 (all tones and individual tones) than TD children. This was in agreement with previous results of adults with CP and dysarthria (Jeng et al., 2006; Patel, 2003). The group and tone differences of F0 were assessed with a mixed-model analysis of variance. Mauchly's test indicated that the assumption of sphericity had been violated, $\chi^2(5) = 11.50$, $p = .04$, and therefore, degrees of freedom were corrected using Greenhouse–Geisser estimates of sphericity ($\varepsilon = .65$). Results showed a significant main effect of tone, tone: $F(1.95, 25.31) = 22.30$, $p < .001$; group: $F(1, 13) = 0.43$, $p = .52$. The Group × Tone interaction was not significant, $F(1.95, 25.31) = 0.94$, $p = .40$. The result indicated that children from the CP group possessed similar ability as TD children to differentiate the four tones, which was probably related to their moderate severity of CP. To investigate the relationship among the four tones, Bonferroni's post hoc tests showed significant differences among all pairwise tone comparisons ($p < .05$; see Appendix C), except for tone 1 and tone 4, with the highest mean F0 in tone 1 ($M = 274.03$ Hz) or tone 4 ($M = 274.88$ Hz), followed by tone 2 ($M = 249.36$ Hz), and tone 3 ($M = 234.22$ Hz). The relative relationships among the four tones observed in the current study paralleled the pattern of adult speakers with CP reported by Jeng et al. (2006), in which tone 1 (high level) had the highest mean F0, followed by tone 4 (high falling), tone 2 (high rising), and tone 3 (low falling–rising).

Comparing the mean slopes of tone 2 and tone 4, the results indicated that children with CP demonstrated a steeper slope of tone 2 and a shallower slope of tone 4 than TD children. Consistent with the overall level of F0 contour developed by Chao (1948), both the CP and TD groups in the current study showed a steeper slope of tone 4 (high falling) as compared to the slope of tone 2 (high rising). Generally, the slopes of tone 2 and tone 4 in TD children are expected to be steeper than those in children with CP. In this study, the slope of tone 2 in children with CP was slightly steeper than that in TD children, which might be related to the faster speech rate in children with CP mentioned above. However, Xu (1998) indicated that F0 slope did not vary as a function of speech rate in normal speakers. This needs to be further examined in the future. Moreover, the unbalanced distribution of children in CP and TD groups and the limited data of syllables with tone 2 are also possible causes.

In order to discern prosodic adequacy, mean standard deviation and range of standard deviation in F0 (all tones and individual tones) and pitch slope (tone 2 and tone 4) in both groups were calculated and compared using an independent-samples t test (see Appendix D). The results indicated that there were no significant group differences in the variability of F0 (all tones and individual tones), slope of tone 2, and slope of tone 4 ($p > .05$). Descriptive data suggested that the CP group showed higher variability in all tones and individual tones than the TD group. This finding differed from Hardy (1983), Irwin (1955), Murry (1983), and Rosenbek and La Pointe (1978), but was consistent with the report for severe dysarthric speakers reported by Schlenck, Bettrich, and Willmes (1993). A plausible explanation for this finding was that moderate and severe dysarthric speakers might attempt to use exaggerated prosodic contrasts to increase their speech intelligibility.

Appendix E summarizes the measures that showed significant differences between children with CP and TD children. In general, the variables in the articulatory-phonetic subsystem were more sensitive for distinguishing children with CP from TD children. To determine which factors might affect the perception of speech, correlations between individual variables and speech intelligibility scores were examined.

Correlates of Speech Intelligibility in the CP and TD Groups

Correlation coefficients of each variable for sentence and word intelligibility in children with CP and TD children (see Table 6) were determined. Since it was difficult to detect a significant correlation between speech intelligibility and other variables due to the small sample size and the large individual differences, correlations higher than $r = .07$ were reported. In addition, correlation coefficients of pairwise correlations among variables in the two groups are shown in Appendix F and Appendix G.

Correlations in the CP Group

Articulatory-phonetic subsystem. The accuracy rates of /i/ and stop consonants were significantly correlated with sentence intelligibility, and the accuracy rates of nasals, fricatives, labials, /m/, /x/, and tone 3 were significantly correlated with word intelligibility (see Table 6). In addition, sentence intelligibility was highly correlated with accuracy of nasals, /x/, and tone 3, whereas word intelligibility was highly correlated with FCR, VAI, F2 slope of /ɪo/, and the accuracy rates of all vowels, stops, velars, /p/, and all tones. VSA, FCR, and VAI were highly correlated with one another and served a similar function. However, sentence and word intelligibility had no correlation with VSA, which did not conform to the findings of previous studies (Liu et al., 2005; Turner, Tjaden, & Weismer, 1995; Weismer et al., 2001). This difference might be due to the expression of FCR and VAI as ratios, which could reduce speaker-related variability (Adank, Smits, & van Hout, 2004) and thus weaken large individual differences among children with CP. Moreover, although there was no significant difference in the accuracy of all tones between the two groups, this measure was significantly correlated with the word intelligibility of children with CP. Since Mandarin is a tonal language, this was a reasonable finding and suggests that children in the CP and TD groups might possess a similar ability to use tone accurately. However, tonal accuracy seemed to play a more important role in speech intelligibility for children with CP. Furthermore, among the major lexical tones, the accuracy rate of tone 3 (low falling) was significantly correlated with word intelligibility and highly correlated with sentence intelligibility of children with CP. Further research is required to determine the connection between the accuracy of tone 3 and speech intelligibility.

In the articulatory-phonetic subsystem, the focus was on the properties of vowel productions, supplemented by the perceptual information on consonant and tonal accuracy. Studies that focus on the contribution of the acoustic properties of consonants to the speech intelligibility in children with CP are necessary. For example, voice onset time of aspirated and unaspirated stops might be a suitable measure for further investigations, since the accuracy rates of stop consonants were observed to have high or significant correlations with sentence and word intelligibility in children with CP.

Phonatory subsystem. SNR was significantly and negatively correlated with sentence intelligibility. This finding was different from the expectation that there should be a positive correlation between SNR and speech intelligibility. Further studies with more participants are needed to obtain a more reliable conclusion. In addition, contrary to expectations, statistical results indicated that, in the CP group, sentence intelligibility had a high positive correlation with shimmer and jitter. It was possible that phonatory variables would be more highly correlated with judgments of voice quality, which were not obtained in this study. A strong correlation between vowel duration and speech intelligibility in adult speakers with CP has been demonstrated (Ansel & Kent, 1992; Rong, Loucks, Kim, & Hasegawa-Johnson, 2012). However, in the present study, vowel duration had no correlation with sentence and word intelligibility, which is consistent with the finding of Lee et al. (2014). Future studies are needed to clarify the influence of vowel duration on the speech intelligibility of children with CP.

Prosodic subsystem. Sentence intelligibility was highly and negatively correlated with speech rate (all syllables), F0 of tone 2, and F0 of tone 3. In addition, word intelligibility was highly and negatively correlated with slope of tone 2 (high rising). The negative correlation between speech rate (all syllables) and sentence intelligibility suggested that a faster speech rate might reduce the intelligibility of the sentence. As to pitch slopes, the negative correlation between slope of tone 2 and word intelligibility was very likely to be biased by the large variation in slope of tone 2 of each child in the CP group and the few tokens of syllables with tone 2, which was less than half of the tokens of syllables with tone 4 (high falling). Unlike slope of tone 2, slope of tone 4 was positively correlated with word intelligibility, though not significant, and this was consistent with the expectations.

Table 6. Correlation of speech variables and speech intelligibility for Mandarin-speaking children with cerebral palsy (CP) (n = 6) and typically developing (TD) children (n = 9).

Variable	CP Sentence intelligibility	CP Word intelligibility	TD Sentence intelligibility	TD Word intelligibility
Articulatory-phonetic subsystem				
VSA	0.06	0.37	0.23	−0.22
F2i/F2u ratio	0.13	0.45	−0.21	−0.07
FCR	−0.64	−0.79[a]	−0.12	0.18
VAI	0.68	0.76[a]	0.15	−0.19
F2 slope /aɪ/	−0.18	0.02	0.28	0.16
F2 slope /ɪa/	0.06	−0.68	0.47	0.10
F2 slope /ɪo/	0.44	0.79[a]	0.36	0.32
Accuracy of all vowels	0.60	0.71[a]	0.22	0.34
Accuracy of single vowels	0.45	0.37	−0.22	−0.04
Accuracy of diphthongs	0.62	0.27	0.61	0.39
Accuracy of frequently occurring vowels				
/i/	0.92*	−0.21	—	—
/u/	—	—	—	—
/a/	−0.35	−0.33	0.66	−0.35
/ə/	0.43	0.69	−0.39	0.31
/ɨ/	0.09	0.29	—	—
/aʊ/	0.19	−0.20	−0.40	−0.22
/ʊa/	0.35	0.38	0.22	0.74*
Accuracy of categorized consonants				
Stop	0.93*	0.76[a]	0.58	0.38
Nasal	0.81[a]	0.98**	−0.28	−0.06
Fricative	0.58	0.81*	−0.48	0.45
Affricate	0.33	0.43	−0.23	−0.04
Lateral	0.50	0.21	0.10	−0.53
Labial	0.55	0.84*	0.45	0.41
Alveolar	0.56	0.58	−0.44	0.15
Velar	0.68	0.80[a]	0.39	−0.02
Accuracy of frequently occurring consonants				
/p/	0.60	0.79[a]	0.17	0.23
/p^h/	0.35	0.39	0.65	0.40
/m/	0.35	0.87*	−0.20	−0.23
/t/	0.43	0.35	−0.39	0.04
/t^h/	−0.16	−0.04	0.66	−0.35
/l/	0.50	0.21	0.10	−0.53
/x/	0.78[a]	0.96**	−0.39	0.04
/ts/	−0.31	−0.08	0.14	0.63
Accuracy of all tones	−0.29	0.80[a]	0.30	0.07
Accuracy of individual tones				
Tone 1	−0.42	0.31	—	—
Tone 2	0.12	0.46	0.51	0.35
Tone 3	0.79[a]	0.99**	0.07	−0.38
Tone 4	−0.61	0.63	−0.22	−0.35
Neutral tone	−0.41	−0.41	0.46	0.49
Phonatory subsystem				
Vowel duration	0.23	−0.06	−0.33	0.02
SNR	−0.92*	0.17	−0.42	−0.32
Jitter	0.71[a]	−0.56	0.49	−0.02
Shimmer	0.86[a]	−0.47	0.44	0.40
Prosodic subsystem				
Speech rate (all syllables)	−0.83[a]	−0.41	0.44	−0.05
Speech rate (intelligible syllables)	−0.23	0.20	0.57	−0.03
F0 of all tones	−0.63	−0.28	−0.15	−0.50
F0 of tone 1	−0.68	−0.22	−0.18	−0.24
F0 of tone 2	−0.84[a]	−0.38	−0.17	−0.42
F0 of tone 3	−0.81[a]	−0.57	−0.22	−0.66
F0 of tone 4	−0.52	−0.32	−0.06	−0.59

(*table continues*)

Table 6. *(Continued).*

Variable	CP		TD	
	Sentence intelligibility	Word intelligibility	Sentence intelligibility	Word intelligibility
Pitch slope				
Slope of tone 2	−0.33	−0.79[a]	0.22	0.14
Slope of tone 4	0.19	0.68	0.18	−0.28

Note. Em dashes indicate the correlation cannot be calculated, as the accuracy rates in this item reached 100% for all participants. VSA = vowel space area; FCR = formant centralization ratio; VAI = vowel articulation index; SNR = signal-to-noise ratio.

[a]High correlation between speech intelligibility and individual variable ($r > .07$).

*$p < .05$. **$p < .01$.

Ohata, Tsuboyama, Haruta, Ichihashi, and Nakamura (2009) reported that higher F0 might reflect the severity of overall speech motor impairment in speakers with CP; therefore, F0 was expected to have an influence on the speech intelligibility of children with CP. In the present study, the strong correlation between sentence intelligibility and F0 was revealed in the high rising tone and the low falling tone in children with CP. The current finding suggested these two tones had greater influence than other tones on sentence intelligibility and sentence intelligibility decreased with the increased mean F0 of these two tones. This finding might be associated with the higher mean F0 and the shorter vowel duration in children with CP. It was plausible that the child might not have enough time to shift from the high mean F0 to a low pitch for the low falling tone within a shorter vowel duration (Xu, 1997) and thus affect the intelligibility of speech. Nevertheless, due to the small sample size, this connection should be regarded with caution. Studies with more participants are required to determine the relationship between F0 and speech intelligibility of child speakers with CP. In addition, the relationship between vowel duration and mean F0 of the low falling tone should be taken into consideration in future studies.

To examine the rationale for the classification of the speech subsystem in the present study, a correlation analysis of all pairwise combinations of selected variables was performed (see Appendix F). Significant correlations were frequently found among variables in the same speech subsystem, and only a few instances of correlations were found across different subsystems, indicating that the classification used in the current study was reasonable.

Correlates in the TD Group

In the TD group, no significant correlations were revealed between speech intelligibility and individual variables (see Table 6); only the accuracy rate of /ʊa/ was significantly correlated with word intelligibility. As shown in Appendix G, significant correlations were detected among variables in the same speech subsystem. Moreover, mean F2 slope of /aɪ, ɪa, ɪo/ was observed to have a significant correlation with speech rate (intelligible syllables), and F0 of all tones was significantly correlated with SNR and shimmer.

A summary of the findings is listed in Appendix H. For children with CP, the three speech subsystems seemed to be equally important for sentence intelligibility, whereas measures of the articulatory-phonetic subsystem (e.g., FCR, VAI, F2 slope of /ɪo/, accuracy of all vowels, and accuracy of all tones) seemed to have more influence on word intelligibility. A similar pattern was not observed in TD children, and the significant measures were more evenly distributed among the three speech subsystems. It would seem reasonable that all aspects of speech production potentially contributed to better speech intelligibility in TD children. The current results suggest that, for children with CP, better performance in articulatory-phonetic features resulted in noticeably higher intelligibility in word productions. Nevertheless, for intelligibility on a larger scope (i.e., sentence), the importance of articulatory-phonetic features was weakened, and listeners seemed to rely more on phonatory as well as prosodic features and context clues in judging speech intelligibility.

Discussion

The primary points of discussion are the comparison with previous research, the value and implications of the subsystem approach, and the general prospects for cross-language research on speech disorders in children with CP.

Comparison of the Current Findings With Those of Lee et al.

Children with CP in the present study were similar to those of Lee et al. (2014) with regard to age. However, the sample size of the current study was smaller than that of Lee et al. (2014). As to the TD control group, unlike Lee et al. (2014), the current study included younger TD children at 62 to 73 months with the anticipation that the competence of speech articulation of CP children should be comparable to that of younger TD children.

With respect to stimuli, both the current study and that by Lee et al. (2014) conducted acoustic analysis and intelligibility judgment based on the speech data from word repetitions. In addition to words, speech data from sentences were also used in the present study for speech rate calculation and intelligibility judgment. When conducting intelligibility judgments, listeners in Lee et al. (2014) could hear the sound file of only one child, whereas one listener in the current study was allowed to hear the sound file of more than one child. Because the word and sentence stimuli tested in the present study were randomly chosen by the system automatically and were different for each individual child, listeners could not become familiarized with the speech stimuli.

As to measure selection, all measures in Lee et al. (2014), except for A1-P1, were analyzed in the current study. Additional acoustic and perceptual measures, including F2i/F2u ratio, FCR, VAI, jitter, shimmer, speech rate, pitch slope, and phonetic accuracy rates of vowels, consonants, and tones were included in the present study to compare with the previous findings and to examine if language-specific characteristics existed. Because A1-P1 was reported to account for a minimal variance in speech intelligibility in Lee et al. (2014), A1-P1 was not included in this study.

Based on different study expectations, the measures in the two studies were classified into different speech subsystems. In Lee et al. (2014), three speech subsystems (i.e., articulatory, velopharyngeal, and laryngeal) corresponded to the three different portions and functions of the supralaryngeal cavity. Vowel space, F2 slope, and vowel duration were in the articulatory subsystem, A1-P1 was in the velopharyngeal subsystem, whereas SNR and mean F0 were in the laryngeal subsystem. On the other hand, in the current study, articulatory-phonetic, phonatory, and prosodic subsystems were considered. The articulatory-phonetic subsystem incorporated acoustic (i.e., VSA, F2i/F2u ratio, FCR, VAI, and F2 slope) and perceptual (i.e., phonetic accuracy rates of vowels, consonants, and tones) measures associated with articulation and represented the same function as the articulatory subsystem in Lee et al. (2014). The phonatory subsystem covered respiratory control (i.e., vowel duration) as well as voice quality (i.e., SNR, jitter, and shimmer) and was generally relevant to the laryngeal subsystem in Lee et al. (2014). Since vowel duration involves one's ability to regulate breathing while producing speech, it was classified into the phonatory subsystem instead of the articulatory-phonetic subsystem in the current study. Tones in Mandarin were expected to show significant group contrasts and to be correlated with speech intelligibility. Therefore, the measures such as mean F0, pitch slope, and speech rate were classified into the prosodic subsystem in the present study.

Significantly smaller VSAs in Mandarin speakers with CP were observed in the present study and in Liu et al. (2005). The significance of VSA in differentiating the CP and TD groups observed from Mandarin-based studies provides strong support to the finding of Lee et al. (2014), even though the VSA in Mandarin is inherently smaller (with three corner vowels) than that in English.

Significant group contrasts were found in vowel duration (CP > TD) in English-speaking children. However, in Mandarin speakers, the relationship of vowel duration between participants in the CP and TD groups exhibited contrary patterns in Jeng et al. (2006) and in the current study. That is, the participants with CP in Jeng et al. (2006) had longer vowel duration than healthy participants, whereas the participants with CP in the present study had shorter vowel duration than healthy participants. Possible reasons might be associated with the small sample size in the present study, which led to reduced statistical power and made it difficult to detect significant group differences. In addition, the different speech stimuli in Lee et al. (2014) and in the present study might give rise to the diverse relationships of vowel duration between children with CP and TD children. The speech stimuli of Lee et al. (2014) were all single words, whereas those of the present study were in the form of word combinations, which sound more natural than single words for children. Word combinations were more challenging than single words for children with CP to repeat in a limited breath group and therefore generated a shorter vowel duration.

In the present study and in Lee et al. (2014), no significant differences between the CP and TD groups were presented in SNR, and no significant relationship was found between SNR and word intelligibility. Further examination was conducted based on Mandarin data with regard to the relationship of SNR and sentence intelligibility. A significant and negative correlation between SNR and sentence intelligibility was detected, but this finding might be biased by the small sample size and the large individual differences.

The universal pattern in terms of a higher mean F0 in individuals with CP as compared to their TD counterparts was observed in Mandarin (the present study; Jeng et al., 2006) and English (Lee et al., 2014) speakers.

Consistent with the finding of Lee et al. (2014), the articulatory-phonetic subsystem of the current study was found to be sensitive in detecting differences between children with CP and TD children, even though the measures analyzed in the current study and in Lee et al. (2014) were not exactly the same. In English data, significant group contrasts were all presented in measures in the articulatory subsystem (i.e., VSA, vowel duration, and F2 slope). On the other hand, in Mandarin data, significant group contrasts were observed in VSA, F2i/F2u ratio, FCR, VAI, jitter, and several perceptual measures (i.e., accuracy of all vowels, single vowels, /ə/, /ɨ/, stops, nasals, affricates, alveolars, tone 3). All measures mentioned above, except for jitter, were from the articulatory-phonetic subsystem.

For both Mandarin and English data, most variables that exhibited significant group contrasts did not necessarily have significant correlation with speech intelligibility. For example, VSA was effective in distinguishing the CP and TD groups for English speakers (Lee et al., 2014) and Mandarin speakers (the present study; Liu et al., 2005), but only the speakers with CP in Liu et al. (2005) demonstrated significant and positive correlation between VSA and speech intelligibility. However, exceptions were observed in a few measures associated with the articulatory subsystem in Lee et al. (2014) and in the current study. Among all segmental measures in the current study, only the accuracy rates of stops and nasals demonstrated significant group differences and had a positive and significant correlation with sentence and word intelligibility, respectively. This was different from the finding of Lee et al. (2014) that F2 slope was the only measure in the articulatory subsystem that exhibited significant group contrasts and accounted for the largest variance in speech intelligibility. In the current study, the F2 slope of /ɪo/ was detected to be positively and significantly correlated with word intelligibility. Nevertheless, the relationship between the F2 slope of /ɪo/ and word intelligibility was hard to determine and requires further examination, because the sample size of this study was small and the number of vowel productions between the CP and TD groups was unbalanced. In addition to F2 slope, mean F0 accounted for 8.3% of the variance in intelligibility of English data, but no significant correlation between mean F0 and speech intelligibility was found in Mandarin. Possible reasons might be related to the different materials used for data measurement and the small sample size.

Major findings from Mandarin- and English-based studies can be summarized as follows. First, both Mandarin and English speakers showed a significant difference in VSA between the CP and TD groups. Prior studies based on Mandarin data have indicated a significant correlation between VSA and word intelligibility, but this was not supported by the current result as well as Lee et al.'s (2014) finding and requires further investigation. Second, previous studies of both Mandarin and English have reported that speakers with CP had longer vowel durations compared to normal speakers; however, this pattern was not observed in the present study. Further studies are needed to clarify the relationship of vowel duration between speakers from the CP and TD groups. Third, individuals with CP from both Mandarin and English environments tended to have higher mean F0 than their TD counterparts.

Comparison of the Current Findings With Those in Other English-Based Studies

As compared with English, there are several differences in segmental and suprasegmental characteristics in Mandarin that may lead to different speech findings in children with dysarthria. First, in Mandarin, there are only three corner vowels (i.e., /i, a, u/), compared to the four corner vowels (i.e., /i, æ, u, ɑ/) in English, thus resulting in a smaller VSA. However, the prominence of vowel space also appears to hold true for Mandarin based on the significant differences between children with CP and TD children in the present study.

Secondly, regarding the F2 frequency, in the diphthong /aɪ/, the main vowel /a/ in Mandarin is a central vowel. However, the main vowel /ɑ/ in English is a back vowel. This may result in a shallower F2 slope in Mandarin during the transition period of diphthong and make it difficult to detect significant group contrasts or weaken the correlational link between F2 slope and speech intelligibility. This expectation is supported by the current results that the mean F2 slope of /aɪ, ɪa/ showed no statistically significant group differences or correlations with speech intelligibility.

Thirdly, unlike English, affricates are prominent in frequency of occurrence in Mandarin. Since affricates and fricatives require precise articulation that ensures the generation of turbulence noise and are demanding in production (Chen & Stevens, 2001), it is expected that, as compared to TD children, significantly lower accuracy rates in affricates and fricatives would be found in children with CP and thus influence speech intelligibility. In the present study, both fricatives and affricates were found to have the lowest accuracy rates in both CP and TD groups, but only affricates produced by children with CP exhibited a significantly lower accuracy rate than TD children. It could be inferred that children from the TD and CP groups encountered difficulties when producing fricatives and affricates at this stage, but the pronunciation of affricates was even more difficult for children with CP. Particular difficulties for fricatives and affricates have been noted in English (Ansel & Kent, 1992), Cantonese (Whitehill & Ciocca, 2000a, 2000b), and Mandarin (Liu, Tseng, & Tsao, 2000). Click languages and languages with many fricatives, affricates, or consonant clusters are expected to be challenging to speakers with CP. However, all consonants are potentially affected, especially when the oral motor system is severely involved.

Finally, with respect to the suprasegmental characteristics in Mandarin, tones play a crucial role in distinguishing syllable meaning. Therefore, the accuracy rates of tones and the slopes of the two distinctive tones (i.e., tone 2 and tone 4) are expected to be significantly different between children with CP and TD children and have a positive correlation with speech intelligibility. Contrary to expectations, none of the accuracy rates of all tones and individual tones showed significant differences between children with CP and TD children. This was likely associated with the moderate level of severity of CP and the generally high tone accuracy for children in the CP group. Moreover, in the present study, the slope of tone 2 was found to be negatively correlated with word intelligibility, which was contrary to our expectations. Further investigation with a larger sample size and more speech data is required to clarify the relationship between the slope of tone 2 and word intelligibility.

Effects of CP on Speech Production Across Languages

Modest progress has been made toward the goal of identifying language-general and language-specific effects on speech production in CP. Obstacles to progress include: (a) very few reports have been published on CP in different languages, (b) studies vary widely in the methods used to study and characterize speech disorders, and (c) the population of children with CP is highly heterogeneous with respect to speech disorders, making it difficult to discern specific effects of native language. The heterogeneity just mentioned is related in large part to variations in type and severity of the neurologic disorder along with characteristics such as age. Especially for severe involvement, it is likely that all subsystems are impaired (Nordberg, Miniscalco, & Lohmander, 2014; Puyuelo & Rondal, 2005; Schölderle et al., 2016). Given these caveats, the following tentative conclusions are offered on the issue of language-related differences in the speech disorders associated with CP.

Vowel articulation often is impaired and has been shown to be highly correlated with intelligibility measures (Higgins & Hodge, 2002; Hustad et al., 2010; Kim, Hasegawa-Johnson, & Perlman, 2011; Liu et al., 2005). Among the features most consistently found to be affected are production of the extreme or point vowels (and therefore the VSA), which reflect the speaker's ability to move the tongue body to its articulatory extrema (i.e., range of motion). Limitations on vowel production in CP have been noted in English (Fox & Boliek, 2012; Hustad et al., 2010), Mandarin (Liu et al., 2000), Kannada (Narasimhan, Nikitha, & Nikita, 2016), and Korean (Sim & Park, 1998). It appears that production of the extreme vowels is very likely a language-general feature for moderate-to-severe oral articulatory involvement. Because languages differ in their number of vowels and diphthongs, depending on the language in question, various adjustments in tongue body and lip configuration are required to produce the full set of vowels. Vowel-rich languages are expected to pose a greater risk of vowel overlap and, therefore, perceptual confusions (Kim et al., 2011). Diphthongs, which also vary in number across languages, place additional requirements on articulation because of their dynamic nature.

Voice disorders occur frequently and take several different forms, including breathiness, strain-strangle, harshness, fatigue, limited range of fundamental frequency, and atypical mean fundamental frequency (Davis, 1987; Falk, Chan, & Shein, 2012; Park, Park, & Kim, 2004; Schölderle et al., 2016; Workinger & Kent, 1991). Voice disorders may be language general and potentially could interfere with tone production in languages such as Cantonese and Mandarin. The relationship between voice disorders and tone production needs further study.

Prosody is often affected, with the nature of the disturbance depending on the language. Specific effects have been described for intonation and stress patterns in English (Kuschmann et al., 2017; Patel, 2003, 2004; Patel, Hustad, Connaghan, & Furr, 2012), tone production in Cantonese (Ciocca, Whitehill, & Ng, 2002; Ciocca, Whitehill, & Yin, 2004), tone production in Mandarin (Jeng et al., 2006), prosody in German (Schölderle et al., 2016), and prosody in Spanish (Puyuelo & Rondal, 2005). It is clear from these studies that prosody is a vulnerable feature of the speech disorder in CP, and cross-language comparisons may illuminate language variations in these disturbances.

Implications of Subsystem Approach

The multiple speech subsystems approach provides a comprehensive and systematic framework to (a) describe the characteristics of individuals with speech disorders from different language backgrounds, (b) observe the progression history of speech disorders with natural maturation and aging, and (c) identify general directions and strategies for the improvement of clinical assessment and treatment. Because the natural progression of the speech disorder is best addressed in a longitudinal design, this preliminary study cannot speak directly to this issue. However, the methods and measures defined in the present study are informative for future studies investigating the effects of maturation and aging on the speech characteristics of individuals with CP. Providing directions or suggestions to improve clinical interventions is an important motivation behind the present study, but it is not the main focus of this report. Rather, the current study design is more relevant to discovering the effects of CP on Mandarin speech productions.

Limitations and Future Study

This study was an investigation of speech production in a small group of children with CP. The design of a larger sample size with a range of dysarthria severity should be useful to clarify whether the findings are related primarily to a particular severity of dysarthria or can be generally applied to various levels of severity. It also would be informative to conduct longitudinal studies to determine how speech production changes in children with CP as the result of treatment and/or maturation. A few points regarding recording procedures and measure selection can be taken into consideration for further examination. First, when making recordings, oral prompts from the examiner should be reduced to minimize external sources of variability in the speech data. Second, audibility of speech signals is crucial to intelligibility judgments and should be verified. For example, it may be advisable for future studies to measure the sound level pressure of the speech signals in order to draw more valid conclusions about which variables or subsystems are strongly correlated to speech intelligibility. Third, to ensure a consistent mic-to-mouth distance, a lavalier microphone taped to the child's forehead (Clair-Auger, Gan, Norton, & Boliek, 2015) might be a better choice for collecting speech data. Fourth, future studies could provide information of transcription errors among different listeners (judges) to guide acoustic analysis. For example, vowel confusions could be more informative than vowel space measures on speech perception, and consonant confusions with respect to place, manner, or voicing contrasts could serve as a useful reference for further decisions on acoustic analysis. Finally, the reports would be more comprehensive if measures associated with respiration and resonance are included. Compromised respiratory function and speech breathing have been noted and can have profound effects on the production of multisyllabic sequences (Hardy, 1967; Solomon & Charron, 1998) and the characteristics of babbling (Levin, 1999). Aerodynamic analysis of voice is an index that can assess the functions of the respiratory system and serves as an important indicator for the differentiation of a pathological voice from a normal one. Due to methodological constraints associated with setting up and calibrating equipment, aerodynamic analysis of voice is not addressed in this study, but should be considered for future research. Another issue deserving of careful study is resonance. Severe disorders of velopharyngeal function can greatly reduce the phonetic contrasts among consonants and cause reduction of intelligibility. Measures that reflect velopharyngeal function are therefore of high interest. An obstacle to this line of research is that the acoustic correlates of nasalization vary with several factors, including anatomical differences across individuals, the area of velar coupling, vowel identity, and phonetic context. Lee et al. (2014) have measured A1-P1 to quantify the degree of nasalization of oral vowels in child speakers, but it was reported to account for a minimal variance in intelligibility scores. It is uncertain that any single acoustic measure is a satisfactory index across speakers and phonetic contexts. Because it can be difficult to identify correlates of nasalization across different vowels, the vowel /i/ often is preferred for analysis (Kataoka, Michi, Okabe, Miura, & Yoshida, 1996; Lee, Ciocca, & Whitehill, 2003) for the reasons that: (a) for a given velopharyngeal area, the effect of acoustical coupling is greater for high than for low vowels, and (b) the nasal pole near 1 kHz in /i/ usually is prominent because it is distant from F1 and F2. Much of the work to date pertains to adult speakers with normal speech. Acoustic measures of nasalization are important, but further work is needed to refine measures suitable for diverse speaker populations.

Conclusion

Neuromotor disorders often affect several aspects of speech production. The present study investigated the speech characteristics of Mandarin-speaking children with moderate dysarthria secondary to CP with a multiple speech subsystems approach, which involved articulation, phonation, and prosody, and examined the relationship of individual subsystems to intelligibility. As compared to phonatory and prosodic subsystems, the articulatory-phonetic subsystem is more sensitive in representing the impaired speech motor control in children with CP and is more effective in accounting for the variation of word intelligibility. However, for sentence intelligibility, all three speech subsystems are involved in children speaking Mandarin. The current results regarding the predominant involvement of the articulatory subsystem in speech production parallel findings of previous studies on child as well as adult speakers. This similarity provides a theoretical basis for improving speech intelligibility in children with dysarthria due to CP cross-linguistically and suggests that the assessment and treatment with respect to articulation used for Western languages can be generally applied to other languages such as Mandarin. However, these clinical assessment and treatment techniques should be used with caution when speakers are from different language backgrounds. For example, the frequent occurrence of affricates, the significantly lower accuracy rate of affricates in children with CP relative to TD children, and the significant correlation of tones with speech intelligibility observed from Mandarin should be taken into consideration.

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Appendix A

Number of Syllables and Sentences Used in Acoustic and Perceptual Measures, Percent Intelligibility, and Speech Rate for Mandarin-Speaking Children With Cerebral Palsy (CP) and Typically Developing (TD) Children.

	Variable measurements	Speech intelligibility judgments		Speech rate
Child	Usable syllables in 39 word combinations	Usable syllables in 39 word combinations	Number of sentences (total syllables)	Sentences (total syllables)
CP1	76	79	23 (80)	23 (80)
CP2	79	79	20 (80)	20 (80)
CP3	69	82	14 (80)	14 (80)
CP4	77	81	23 (80)	23 (80)
CP5	79	79	23 (80)	23 (80)
CP6	72	81	—	—
TD1	66	68	36 (160)	34 (153)
TD2	73	84	32 (160)	29 (147)
TD3	76	79	32 (160)	30 (147)
TD4	44	55	32 (160)	25 (128)
TD5	61	69	36 (160)	13 (61)
TD6	57	82	36 (160)	33 (147)
TD7	58	58	36 (160)	27 (123)
TD8	62	81	36 (160)	36 (160)
TD9	73	75	36 (160)	32 (141)

Note. Column 2 indicates the number of usable syllables in 39 word combinations for variable measurements (all the acoustic measures and phonetic accuracy rates), excluding syllables with unacceptable recording quality or high background noise. Column 3 indicates the number of usable syllables in 39 word combinations for intelligibility judgment. Column 4 indicates the number and total syllables (in parentheses) of sentences for intelligibility judgments. Column 5 indicates the number and total syllables (in parentheses) of sentences for speech rate calculation; fragmented sentences were excluded for TD children. Em dashes indicate no data, as CP6 was unable to perform the sentence repetition task.

Appendix B

Number of Sentences and Total Syllables for Speech Rate Calculation (Based on All Syllables and Intelligible Syllables) for Mandarin-Speaking Children With Cerebral Palsy (CP) and Typically Developing (TD) Children.

Child	Age (years)	Age level of sentence stimuli	Sentence length (in syllables)[a] 3	4	5	6	7	8	Number of sentences (total syllables)	Speech rate (all syllables)	Speech rate (intelligible syllables)
CP1	7	3	12	11	0	0	0	0	23 (80)	2.07	1.87
CP2	4	4	7	6	7	0	0	0	20 (80)	3.21	2.18
CP3	7	7	2	2	2	3	2	3	14 (80)	2.43	2.30
CP4	8	3	12	11	0	0	0	0	23 (80)	2.01	1.66
CP5	6	3	12	11	0	0	0	0	23 (80)	2.95	2.23
CP6	8	—	—	—	—	—	—	—	—	—	—
TD1	5	5	7	10	10	7	0	0	34 (153)	2.05	2.05
TD2	6	6	4	6	8	6	5	0	29 (147)	2.31	2.31
TD3	5	6	5	6	10	5	4	0	30 (147)	2.00	1.93
TD4	5	6	3	6	6	5	5	0	25 (128)	2.08	2.07
TD5	5	5	3	2	4	4	0	0	13 (61)	1.99	1.98
TD6	5	5	7	10	10	6	0	0	33 (147)	2.04	2.04
TD7	5	5	5	8	8	6	0	0	27 (123)	2.23	2.18
TD8	5	5	8	11	10	7	0	0	36 (160)	2.16	2.16
TD9	5	5	8	10	7	7	0	0	32 (141)	2.28	2.24

Note. Em dashes indicate no data, as CP6 was unable to perform the sentence repetition task during this recording session.
[a]Number of sentences.

Appendix C

Bonferroni's Post Hoc Tests Among All Pairwise Tone Comparisons.

Variable	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	—	.01*	.00*	1.00
Tone 2		—	.01*	.00*
Tone 3			—	.00*
Tone 4				—

*$p < .05$.

Appendix D

Mean Standard Deviation for F0 (All Tones and Individual Tones), Slope of Tone 2, and Slope of Tone 4 for Mandarin-Speaking Children With Cerebral Palsy (CP) and Typically Developing (TD) Children.

Variable	CP *M* (*SD*)	CP Range	TD *M* (*SD*)	TD Range	*t*	*p*
F0 of all tones (Hz)	68.72 (23.73)	75.44–599.08	55.69 (12.85)	75.37–599.48	1.39	.19
F0 of tone 1	57.52 (26.36)	75.62–599.08	46.17 (27.02)	75.37–546.70	0.80	.44
F0 of tone 2	60.08 (30.08)	75.66–578.11	38.18 (11.96)	76.20–405.78	1.99	.07
F0 of tone 3	66.41 (33.44)	76.21–598.35	53.14 (14.97)	76.05–598.17	0.91	.40
F0 of tone 4	63.25 (24.54)	75.44–572.18	54.11 (17.06)	75.44–599.48	0.86	.41
Pitch slope						
Slope of tone 2 (Hz)	0.10 (0.05)	0.05–0.57	0.10 (0.04)	0.02–0.62	0.02	.99
Slope of tone 4 (Hz)	0.15 (0.05)	0.03–1.01	0.12 (0.03)	0.05–0.80	1.43	.19

Note. *M* = mean of standard deviation; *SD* = standard deviation of mean standard deviation.

Appendix E

Summary of Significant Differences Between Mandarin-Speaking Children With Cerebral Palsy (CP) and Typically Developing (TD) Children.

- Speech intelligibility
  - Significant variables
    - Sentence (TD > CP)
    - Word (TD > CP)
- Articulatory-phonetic subsystem
  - Significant variables
    - VSA (TD > CP)
    - F2i/F2u ratio (TD > CP)
    - FCR (CP > TD)
    - VAI (TD > CP)
    - Accuracy of all vowels (TD > CP)
    - Accuracy of single vowels (TD > CP)
    - Accuracy of /ə/ (TD > CP)
    - Accuracy of /ɨ/ (TD > CP)
    - Accuracy of stops (TD > CP)
    - Accuracy of nasals (TD > CP)
    - Accuracy of affricates (TD > CP)
    - Accuracy of alveolars (TD > CP)
  - Nonsignificant variables
    - F2 slope /aɪ, ɪo/ (CP > TD)
    - F2 slope /ɪa/ (TD > CP)
    - Accuracy of diphthongs (TD > CP)
    - Accuracy of frequently occurring vowels (i.e., /i, u, a, aʊ, ʊa/) (TD > CP)
    - Accuracy of consonants (i.e., fricatives, laterals, labials, velars) (TD > CP)
    - Accuracy of frequently occurring consonants (i.e., /m, t, t^h, l, x, ts/) (TD > CP)
    - Accuracy of frequently occurring consonants (i.e., /p, p^h/) (CP > TD)
    - Accuracy of all tones (TD > CP)
    - Accuracy of individual tones (i.e., tone 1, 2, 3, 4) (TD > CP)
- Phonatory subsystem
  - Significant variable
    - Jitter (CP > TD)
  - Nonsignificant variables
    - Vowel duration (TD > CP)
    - SNR (TD > CP)
    - Shimmer (CP > TD)
- Prosodic subsystem
  - Nonsignificant variables
    - Speech rate (all syllables) (CP > TD)
    - Speech rate (intelligible syllables) (TD > CP)
    - F0 of all tones (CP > TD)
    - F0 of tone 1 (CP > TD)
    - F0 of tone 2 (CP > TD)
    - F0 of tone 3 (CP > TD)
    - F0 of tone 4 (CP > TD)
    - Slope of tone 2 (CP > TD)
    - Slope of tone 4 (TD > CP)

Note. VSA = vowel space area; FCR = formant centralization ratio; VAI = vowel articulation index; SNR = signal-to-noise ratio.

Appendix F

Correlation Coefficient Matrix of the Significant Speech Variables for Mandarin-Speaking Children With Cerebral Palsy (CP) (n = 6).

Variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Articulatory-phonetic subsystem																		
1. VSA	—	.97**	−.77[a]	.78[a]	−.68	.09	−.21	.50	.59	.37	.08	−.37	−.24	−.06	−.06	.12	.14	.69
2. F2i/F2u ratio		—	−.86*	.86*	−.71[a]	.18	−.20	.63	.60	.31	−.01	−.33	−.17	−.21	−.25	−.04	.08	.66
3. FCR			—	−1.00**	.51	−.56	−.14	−.70	−.70	−.21	.16	.33	.13	.63	.34	.34	.37	−.73[a]
4. VAI				—	−.56	.57	.16	.73[a]	.67	.24	−.22	−.28	−.07	−.64	−.33	−.35	−.34	.71[a]
5. Mean F2 slope of /aɪ, ɪa, ɪo/					—	.07	.28	−.75[a]	.06	−.35	.60	−.36	−.53	.58	.48	.27	−.44	−.24
6. Accuracy of all vowels						—	.87*	.52	.64	.46	−.14	−.40	−.01	−.17	.42	−.12	−.49	.12
7. Accuracy of single vowels							—	.23	.39	.57	−.10	−.29	.08	.06	.64	.13	−.33	−.17
8. Accuracy of diphthongs								—	.27	.49	−.60	.10	.49	−.60	−.36	−.36	.15	.08
9. Accuracy of all tones									—	.38	.49	−.89*	−.66	.70	.82[a]	.30	−.34	.52
Phonatory subsystem																		
10. Vowel duration										—	−.06	−.30	.15	.21	.59	.54	.46	−.18
11. SNR											—	−.81*	−.94**	.96*	.57	.71[a]	−.05	.13
12. Jitter												—	.86*	−.97**	−.81[a]	−.60	.19	−.30
13. Shimmer													—	−.89*	−.53	−.50	.32	−.44
Prosodic subsystem																		
14. Speech rate (all syllables)														—	.73[a]	.92*	.28	−.23
15. Speech rate (intelligible syllables)															—	.82[a]	.02	−.15
16. F0 of all tones																—	.49	−.23
17. Slope of tone 2																	—	−.54
18. Slope of tone 4																		—

Note. VSA = vowel space area; FCR = formant centralization ratio; VAI = vowel articulation index; SNR = signal-to-noise ratio.

[a]High correlation between two different variables (r > .07).

*p < .05. **p < .01.

Appendix G

Correlation Coefficient Matrix of Significant Speech Variables for Mandarin-Speaking Typically Developing (TD) Children (n = 9).

Variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Articulatory-phonetic subsystem																		
1. VSA	—	.53	−.78*	.78*	.35	.26	.01	.52	.41	.08	−.18	.35	.23	.10	.14	.11	.64	.36
2. F2i/F2u ratio		—	−.86**	.84**	.38	.57	.04	.40	.64	.14	.06	.06	−.04	−.34	−.24	.07	.27	.12
3. FCR			—	−1.00**	−.39	−.64	.01	−.64	−.56	−.24	.13	−.28	−.04	.17	.07	−.18	−.52	−.43
4. VAI				—	.41	.65	.01	.65	.55	.22	−.15	.30	.06	−.12	−.02	.19	.54	.45
5. Mean F2 slope of /aɪ, ɪa, ɪo/					—	.39	.00	.53	.31	−.55	−.23	.29	.39	.61	.73*	−.14	.35	.16
6. Accuracy of all vowels						—	.36	.78*	.49	.35	−.17	.01	.11	−.17	−.03	.08	.61	.34
7. Accuracy of single vowels							—	−.09	−.12	.13	.12	−.32	−.02	.16	.14	.23	.61	.14
8. Accuracy of diphthongs								—	.57	.22	−.30	.24	.29	.00	.15	−.04	.55	.37
9. Accuracy of all tones									—	−.08	−.25	.31	.35	−.47	−.29	−.36	.12	−.31
Phonatory subsystem																		
10. Vowel duration										—	.44	−.54	−.61	−.52	−.56	.57	.17	.50
11. SNR											—	−.91**	−.92**	−.05	−.11	.79*	−.32	.37
12. Jitter												—	.81**	.11	.18	−.66	.19	−.28
13. Shimmer													—	.16	.23	−.86**	.34	−.52
Prosodic subsystem																		
14. Speech rate (all syllables)														—	.98**	.17	.28	.37
15. Speech rate (intelligible syllables)															—	.12	.31	.36
16. F0 of all tones																—	.09	.83**
17. Slope of tone 2																	—	.43
18. Slope of tone 4																		—

Note. VSA = vowel space area; FCR = formant centralization ratio; VAI = vowel articulation index; SNR = signal-to-noise ratio.

*p < .05. **p < .01.

Appendix H

Summary of Variables Correlated With Speech Intelligibility for Mandarin-Speaking Children With Cerebral Palsy (CP) and Typically Developing (TD) Children.

CP

- Sentence intelligibility
  - Significantly correlated variables
    - Accuracy of /i/
    - Accuracy of stops
    - SNR
  - Highly correlated variables
    - Accuracy of nasals
    - Accuracy of /x/
    - Accuracy of tone 3
    - Jitter
    - Shimmer
    - Speech rate (all syllables)
    - F0 of tone 2
    - F0 of tone 3
- Word intelligibility
  - Significantly correlated variables
    - Accuracy of nasals
    - Accuracy of fricatives
    - Accuracy of labials
    - Accuracy of /m/
    - Accuracy of /x/
    - Accuracy of tone 3
  - Highly correlated variables
    - FCR
    - VAI
    - F2 slope /ɪo/
    - Accuracy of all vowels
    - Accuracy of stops
    - Accuracy of velars
    - Accuracy of /p/
    - Accuracy of all tones
    - Slope of tone 2
- Significant correlations among variables
    - F2i/F2u ratio: VSA
    - F2i/F2u ratio: FCR
    - F2i/F2u ratio: VAI
    - FCR: VAI
    - Accuracy of all vowels: Accuracy of single vowels
    - Accuracy of all tones: Jitter
    - SNR: Jitter
    - SNR: Shimmer
    - Jitter: Shimmer
    - Speech rate (all syllables): SNR
    - Speech rate (all syllables): Jitter
    - Speech rate (all syllables): Shimmer
    - Speech rate (all syllables): F0 of all tones
- High correlations among variables
    - F2i/F2u ratio: F2 slope
    - FCR: VSA
    - FCR: Slope of tone 4
    - VAI: VSA
    - VAI: Accuracy of diphthongs
    - VAI: Slope of tone 4
    - F2 slope: Accuracy of diphthongs
    - SNR: F0 of all tones
    - Speech rate (intelligible syllables): Accuracy of all tones
    - Speech rate (intelligible syllables): Jitter
    - Speech rate (intelligible syllables): Speech rate (all syllables)
    - Speech rate (intelligible syllables): F0 of all tones

TD

- Sentence intelligibility
  - No significantly correlated variables
- Word intelligibility
  - Significantly correlated variables
    - Accuracy of /ʊa/
- Significant correlations among variables
    - VSA: FCR
    - VSA: VAI
    - F2i/F2u ratio: FCR
    - F2i/F2u ratio: VAI
    - FCR: VAI
    - Mean F2 slope of /aɪ, ɪa, ɪo/: Speech rate (intelligible syllables)
    - Accuracy of all vowels: Accuracy of diphthongs
    - SNR: Jitter
    - SNR: Shimmer
    - Jitter: Shimmer
    - Speech rate (intelligible syllables): Speech rate (all syllables)
    - F0 of all tones: SNR
    - F0 of all tones: Shimmer
    - F0 of all tones: Slope of tone 4

Note. SNR = signal-to-noise ratio; VSA = vowel space area; FCR = formant centralization ratio; VAI = vowel articulation index.