Taylor & Francis
Taylor & Francis Group

Production and perception of mandarin tone in adults with cerebral palsy

JING-YI JENG[1], GARY WEISMER[2], & RAY D. KENT[2]

[1]*Department of Special Education, Tainan Teachers' College, Taiwan, and* [2]*Department of Communicative Disorders & Waisman Center, University of Wisconsin-Madison, Madison, WI, USA*

Abstract

The primary objective of the present study was to document tone production and intelligibility deficits in Mandarin-speaking persons with cerebral palsy (CP). Spastic, athetoid, and mixed types of CP were studied, along with a control group, to investigate the possibility of tone production and intelligibility deficits that were differentially affected by type of CP. Speakers produced a 78-word list that included contrasts for all four Mandarin tones. Intelligibility data were obtained for these words from 26 native speakers of Mandarin, and F0 contour analyses were implemented in CSpeech (Milenkovic) for a subset of the words. Mean tone intelligibility for speakers with CP was 73%, significantly different from the 91% value for control speakers. F0 contour analysis showed that speakers with CP maintained some contrast among the F0 contours for the four tones, but with less distinction than contrasts observed for control speakers. Discussion focuses on the role of tone in a model of the dysarthria associated with CP.

Keywords: *Cerebral palsy, Mandarin, tone production, tone perception*

Introduction

Cerebral palsy (CP) is a nonprogressive neuromuscular disorder caused by damage to the various parts of the developing brain (Mecham, 1996). Speech disorders are commonly found in individuals with CP (Wolfe, 1950; Achilles 1955; Workinger, 1986; Workinger & Kent, 1991), and may include articulatory, resonance, voice, and speech breathing problems. In addition, prosodic abnormalities are observed in speakers with CP, whose speech is often perceived as slow, arhythmic and monotonous (Workinger & Kent, 1991). As an example of the prosodic problem, McDonald (1987) reported that many speakers with CP had difficulty in achieving the perceptual contrast between stressed and unstressed syllables. More recently, speakers with severe CP have been shown to produce sentence-level fundamental frequency (F0) contours with abnormal characteristics, but with sufficient contrast to distinguish declarative from interrogative utterances (Patel, 2002). There is also evidence that persons with CP who are native speakers of Cantonese, a tone

language spoken in various parts of Asia, make errors on certain tones as revealed in listener responses and acoustic analyses of tone-related F0 contours (Whitehill & Ciocca, 2000a, b; Whitehill, Ciocca, & Chow, 2000; Ciocca, Whitehill, & Ng, 2002). This work suggests that speakers with cerebral palsy would be likely to show tone production and intelligibility deficits in other tone languages, as well. In the present study, therefore, the production and intelligibility characteristics of tone are explored in persons with CP who are native speakers of Mandarin, a tone language with more native speakers than any other language in the world.

Mandarin Chinese uses tone contrasts to differentiate meaning at the syllable level. There are four contrastive tones in Mandarin: high level tone (Tone 1), high rising tone (Tone 2), low falling-rising tone (Tone 3), and high falling tone (Tone 4). Chao (1948), using a conventional numerical description, set the pitch values for the four tones as 5-5, 3-5, 2-1-4, and 5-1 for Tones 1 through 4, respectively (see the same descriptive device used for Cantonese tones in Whitehill & Ciocca, 2000b). The numbers represent the pitch height on a five-level scale, in which 1 represents the lowest pitch and 5 represents the highest pitch. These four tone contours are shown schematically in Figure 1.

Tseng (1990) has shown that distinctive F0 contours are the primary cues for tone perception; more recently, the compelling evidence for this position has been reviewed by Wang, Spence, Jongman, and Sereno (1999). In addition to F0 contours, other acoustic variables may contribute to the perception of tone, for example, duration and intensity. Among the four tones, Tone 2 and Tone 3 (if the latter has its "full" shape)[1] are usually longer than Tones 1 and 4, and Tone 4 has the strongest intensity (Ong & Yang, 1997). Although syllable duration and intensity (see Whalen & Xu, 1992) may carry tone information in spontaneous speech, the properties of duration or intensity may be affected by many factors, such as position in an utterance, emphasis, paralinguistic factors, or syntactic structure. It is reasonable to conclude, therefore, that in Mandarin, syllable-level F0 contour is essential to tone perception. Because of the phonemic status of tones in
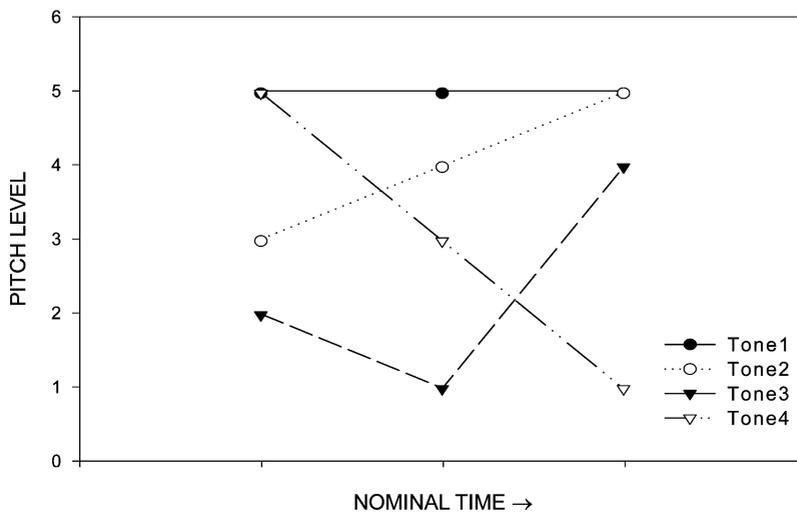

Figure 1. Schematic pitch contours of the four Mandarin tones according to Chao's five-level pitch system.

Mandarin, it can be predicted that tones contribute an important component to speech intelligibility.

For speakers of tone languages, laryngeal control and timing are essential for accurate tone production. The control of F0 is vested in the intrinsic and extrinsic muscles of the larynx, with the cricothyroid (CT) muscle primarily responsible for F0 fluctuations, in combination with actions of the vocalis muscles (VOC) and subglottal pressure (Atkinson, 1978; Hirano, Ohala, & Vennard, 1969; Gay, Strome, Hirose, & Swashima, 1972). The extrinsic muscles of the larynx, such as sternohyoid (SH) and sternothyroid (ST), may play an important role in F0 lowering. Although the specific role of the extrinsic, or strap muscles in F0 control is still unclear (Hirose, 1997: 134), Hallé (1994) has presented evidence implicating SH activity in the lowering characteristics of Tones 2 and 4 in Mandarin. Clearly, however, the intrinsic and extrinsic muscles of the larynx, and possibly the respiratory system, participate in producing the distinctive F0 contours of tone languages. Erickson (1993), using EMG techniques, investigated laryngeal muscle activity in Thai tone production and found that CT, SH and ST were involved in differentiating the tones. In the dysarthria associated with cerebral palsy, where deficits have been reported for the larynx (Workinger, 1986; Workinger & Kent, 1991), it is therefore reasonable to expect some deficit in tone production and hence intelligibility of words differentiated by tone. This is precisely what was found in Cantonese speakers with CP by Whitehill and Ciocca (2000a). In an unpublished study of Mandarin speakers with CP, Wang (1997) found relatively high correlations (r=.86–.93) between measures of tone intelligibility and overall estimates of speech intelligibility for sentences, and also determined that tone intelligibility was higher than overall sentence intelligibility.

The specific purposes of the present study were, (1) to evaluate tone intelligibility in three groups of Mandarin-speaking individuals with CP, as well as in control speakers, (2) to report on the F0 contour characteristics of tone production among these speakers, and (3) to interpret for the same groups of speakers the relationship between tone intelligibility and specific aspects of F0 contours. The three groups of individuals with CP were diagnosed with primarily spastic, athetoid, or mixed symptoms. Cerebral palsy is often categorized according to these subtypes (as well as a primarily ataxic subtype, not studied here), and there has been interest in the dysarthria literature in determining potentially unique speech production and/or intelligibility characteristics for the different types. Platt, Andrews and Young (1980a), Platt, Andrews, and Howie (1980b) and Workinger (1986; Workinger & Kent, 1991), for example, found certain articulatory and voice differences between the spastic and athetoid subtypes, but in many cases the differences were fairly subtle. Workinger and Kent (1991) concluded that the spastic type of CP was associated with more problems in the laryngeal and resonance system, while the athetoid type was associated with greater problems in motor coordination between speech subsystems. In Whitehill and Ciocca (2000b), there were some subtype differences for the error rates of selected phonetic contrast errors but no clear, larger pattern that would associate particular phonetic difficulties with a particular subtype of CP. Tone errors, especially those for the high vs. low level-tone contrast, were frequent among the participants in Whitehill and Ciocca (2000b) and did not seem to favor any of the subtypes. Presumably, the use of balanced numbers of participants in each group and careful examination of the acoustic basis of tone phenomena would extend the current limited understanding of the role of tone production deficits in dysarthria. The current study was undertaken to approach the problem in just this way.

Method

The methods for the present study are in two sections. First, methods are presented for the experiment on tone intelligibility, and second, the approach is described for the F0 analysis of the tone contours.

Tone intelligibility

Speakers

Thirty students with cerebral palsy, all enrolled in the National Chang-Hua Jen-Ai School for Physically Handicapped (CHJAS in Taiwan) participated in the present investigation.[2] Ten of these participants were judged to have (primarily) the spastic type of CP, ten the athetoid type, and ten mixed symptoms. Type of CP was judged by a physical therapist at the school, based on evaluations of posture, facial expression, gait and limb movements. Each group included five male and five female participants. The age of all participants ranged from 17–25 years. The 30 participants with CP covered a wide range of severity, and all had some degree of communication difficulty as described by their teachers. Overall disease severity was not measured for this investigation, but the wide range is reflected in the single word intelligibility scores. These ranged from 4–58% for participants with athetosis, 18–66% for participants with spasticity, and 12–73% for participants with a mixed diagnosis. All participants with CP had hearing thresholds equal to or better than 30 dB HL (pure tone average at 500, 1000, and 2000Hz), and all speakers spoke Mandarin Chinese as their native language. Ten age-matched participants served as a control group (five males and five females). Their ages ranged from 19–28. These speakers were native speakers of Mandarin and had no known neurogenic disease or any sensory difficulty.

Speech sample and recording procedures

The speech sample for evaluation of tone intelligibility included 78 monosyllabic words (Jeng, 2000) that sampled all four Mandarin tones. The speech sample (with the English translation in parentheses) analysed for the F0 characteristics of tone included two sets of tone contrasts: /pɑ1/(eight, bā in Pinyin), /pɑ2/ (pull, bá in Pinyin), /pɑ3/ (handle, bǎ in Pinyin), /pɑ4/ (Dad, bà in Pinyin)/, and /ɕi1/ (west, xī in Pinyin), /ɕi2/ (breath, xí in Pinyin), /ɕi3/ (happy, xǐ, in Pinyin), /ɕi4/ (game, xì in Pinyin). This subset of tone contrasts for the F0 analysis was assumed to be representative of the same tone contrasts in other phonetic environments; Ho (1976) has reported that consonant context and vowel identity have only small effects on F0 characteristics of Mandarin tones, and that the F0 pattern contrasts among the tones are preserved even under these changing phonetic conditions.

Speech samples were recorded in a quiet room using a Marantz PMD 201 cassette recorder and a Shure BG2.1 microphone. Word index cards with Chinese word characters and Chinese phonetic symbols were presented to the speakers in a random order. Speakers were instructed to read the word shown on the card in the form "/di4 i1 tsʰɨ4, #___#, di4 ɛ : ɹ4 tsʰɨ4, #___#, 4 di4san1 tsʰɨ4, #___#, di4 ʂu4 tsʰɨ4, #___#, di4 u3 tsʰɨ4, #___#/". This sequence of four phrases means, "The first time the word is ____", "The second time the word is _____", and so forth until, "The fifth time the word is ____"; the number at the end of each syllable denotes the lexical tone. Thus, each word was repeated five times, and essentially in citation form. The target word appeared in utterance-final position, and could be either of the two syllables /pa/ or /ɕi/, with one

of the four Mandarin tones. Because each participant produced all possible syllable-tone combinations, there were a total of forty word (2 syllables × 4 tones × 5 repetitions) productions for each participant.

Intelligibility evaluation procedure

Tone intelligibility data were obtained from the complete word intelligibility evaluation (Jeng, 2000) of the current participants with CP. The participants in the intelligibility evaluation group included 26 adults (13 males and 13 females) with no experience in listening to dysarthric speech. They were all native speakers of Mandarin Chinese and had no history (by self-report) of hearing problems. Their ages ranged from 25 to 35.

Listeners were asked to write down the words they heard, using Chinese characters, or to transcribe the words phonetically using the Juin-Fuhan method.[3] The stimuli consisted of 78 monosyllabic words spoken by the speakers with CP (see Jeng, 2000) including the eight words described above. The stimuli were presented in randomized sequences and at a comfortable loudness level using the stimulus playback facility in CSpeech, which drove a loudspeaker in a sound-treated booth. For the intelligibility evaluation, the target word was excised from the carrier phrase and this presented as a single word. There were five seconds between each word for the normal speakers, and six seconds between each word for the speakers with CP.

Each listening session included 85 word presentations, which had all been spoken by a single speaker. The 85 words were composed of one randomly selected repetition (from the five repetitions produced for each word) of each of the 78 words, plus seven words randomly selected from this list for reliability. Each listener participated in six or seven sessions, each of which involved listening to a single speaker selected randomly from the four groups of participants. A restriction on this random assignment of listeners to groups was that each listener had to hear at least one speaker from each group, and that all listeners had to contribute responses for each group. Thus all 26 listeners furnished responses to each group, although not to every speaker within each group. This design for the listening part of the experiment, wherein listeners responded to a subset of speaker-participants rather than the whole group, was selected to avoid the listening fatigue that would be likely with the whole-sample presentation and transcription of over 3000 words. In the present design each listener heard and transcribed between 510 and 595 words spoken by six or seven speakers. A given word had to be accurate in all respects to be counted as correct. Tone intelligibility for each speaker was computed as the percentage of correct tone responses for each tone category across all words in the intelligibility test.

Results

Reliability

Of all the words that were presented twice, agreement between the first and second presentations occurred 83% of the time; agreement was defined as an exact word match for the first and second presentations of each reliability item. The contingency correlation coefficient for the paired judgments was .80. These reliability figures seemed reasonable, but a conservative approach to post-hoc evaluation of main effects, in the form of Scheffé tests, was chosen to guard against the possible presence of weak effects.

Tone intelligibility

The mean tone intelligibility scores were 73% across all participants with CP, and 91% for control (normal) speakers. Tone intelligibility scores ranged across the 40 speakers from 33% to 96%. The mean tone intelligibility scores were 66% (range=33–87%), 79% (range=65–89%), and 74% (range=46–88%) for the athetoid, spastic and mixed groups, respectively; the range of tone intelligibility scores across speakers in the control group was 81–96%. A one way analysis of variance (ANOVA) of the speaker means showed a main effect of group on tone intelligibility [$F(3, 36)=6.23$, $p<.05$, $\eta^2=.342$]. Post-hoc Scheffé tests revealed the source of this main effect to be a significant difference between the group with athetosis and the control group ($p<.05$). All other pairwise comparisons between groups failed to reach significance.

Tone intelligibility was compared with other word, sentence, and segment-level intelligibility scores reported in Jeng (2000). Mean word intelligibility, independent of tone intelligibility,[4] across all participants with CP was 34%, as compared to 87% for the control speakers; the corresponding mean sentence intelligibility scores were 33% and 98% for participants with CP and control speakers, respectively (Jeng, 2000). Thus, for the participants with CP, the mean tone intelligibility score was substantially higher than the word and sentence intelligibility scores.

Figure 2 shows the segmental intelligibility scores for consonant and vowels by group (Jeng, 2000) plotted with the tone intelligibility results described above. For the participants with CP, tone and vowel intelligibility appear to be roughly similar and clearly higher than consonant intelligibility. The group differences do not appear to interact
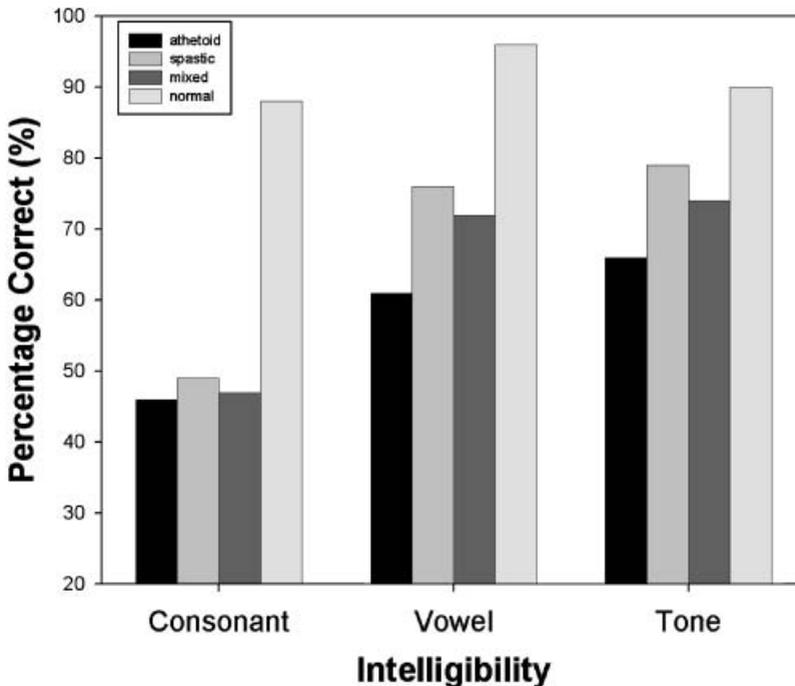

Figure 2. Intelligibility, expressed as percentage correct, for consonant segments, vowel segments, and tone contrasts. The data are plotted by group for each type of intelligibility, in the order athetoid, spastic, mixed, and control, from left to right.

in any meaningful way with the type of intelligibility. When tone intelligibility scores were correlated across all 40 subjects with word and sentence intelligibility scores, the coefficients were moderately high and both significant (r=.76, p<.05, tone vs. word intelligibility; r=.70, p<.05, tone vs. sentence intelligibility).

Tone intelligibility by tone type

A comparison of intelligibility between the four tones was obtained by calculating for each tone the ratio of the number of incorrect responses to the total number of stimuli containing the intended tone. These tone error rates are shown by group in Figure 3. The tone error profiles appear to be similar across the groups of participants with CP, with the highest error rate—more than half of all responses—on tone 3 for all three groups. For the normal group, the highest error rate was observed for tone 2, which has a 3–5 pitch shape.

Tone confusion

Tone confusion data were expressed as percentages, because the four intended tones did not have strictly equivalent representation in the test material. Normalized tone confusion matrices for the four groups are shown in Table I. The intended tones are shown along the horizontal, with tone responses on the vertical. The number in each cell is the percentage of responses for a particular intended tone. The smallest number of actual responses for the confusion matrices in Table I was 3440 for the group with mixed CP, and the largest number was 3617 for the group with spastic CP. In all four groups, and especially in the groups with CP, the most frequent confusions were between Tone 2 and Tone 3. Within the Tone 2-Tone 3 confusions all three groups with CP showed the same asymmetry, with more Tone 2-for-Tone 3 confusions than the reverse; the control group showed the
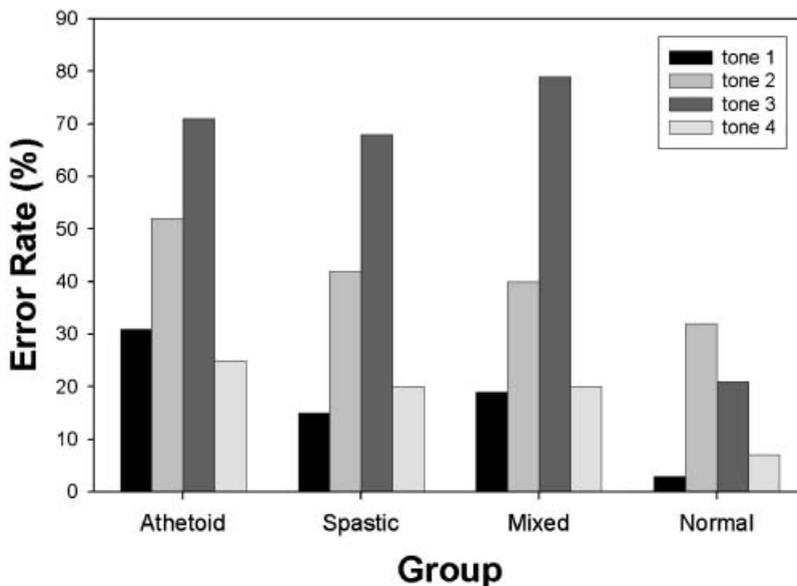

Figure 3. Error rates for the four tones, plotted for the four groups. For each group, the data are plotted from left to right for tones 1 through 4, respectively.

Table I. Normalized tone confusion matrices for the four groups. The number in each cell is the percentage that the stimulus tone (along the horizontal) was heard as the corresponding response (along the vertical). Correct responses are given in bold. Note that tone 0 was never intended, but did contribute a small umber of responses as reported in the matrices; see text for details.

Normal group

| | Tone | RESPONSE | | | |
		Tone **1**	Tone **2**	Tone **3**	Tone **4**
I	0	.0	.0	2.2	.8
N	1	97.1	3.9	4.7	3.4
T					
E	2	2.3	67.9	9.4	.4
N					
D	3	.4	27.9	80.7	3.7
E					
D	4	.2	.3	3.0	91.8

Athetoid group

| | Tone | RESPONSE | | | |
		Tone **1**	Tone **2**	Tone **3**	Tone **4**
I	0	1.3	2.6	.5	2.5
N	1	69.3	16.2	15.2	10.7
T					
E	2	5.2	48.5	44.7	1.8
D					
N	3	8.9	27.5	30.1	9.0
E					
D	4	15.3	5.2	9.6	76.0

Spastic group

| | Tone | RESPONSE | | | |
		Tone **1**	Tone **2**	Tone **3**	Tone **4**
I	0	.7	.0	.5	1.6
N	1	85.0	10.0	15.1	9.1
T					
E	2	5.2	58.9	42.1	2.2
N					
D	3	4.3	28.2	33.2	6.5
E					
D	4	4.8	2.9	9.1	80.6

Mixed group

| | Tone | RESPONSE | | | |
		Tone **1**	Tone **2**	Tone **3**	Tone **4**
I	0	.9	.3	.9	2.2
N	1	81.9	12.3	9.2	9.0

Table I. Continued.

Mixed group

| | Tone | RESPONSE | | | |
		Tone **1**	Tone **2**	Tone **3**	Tone **4**
T					
E	2	4.1	60.1	55.0	1.3
N					
D	3	6.0	25.6	31.1	5.5
E					
D	4	7.1	1.7	3.7	82.0

opposite asymmetry. For the groups with CP, Tone 1 for Tone 2 and 3 errors were also fairly frequent.

F0 analysis of tones

Acoustic Analysis Procedures

F0 contours were extracted with the F0 tracking function provided by CSpeech (Milenkovic, 1996), which is based on an autocorrelation algorithm. The update rate for the F0 tracking function was set to 2 milliseconds (ms). Each automatically-generated F0 contour was inspected for errors (such as doubling or halving errors), which were corrected with a CSpeech algorithm that permits interactive, period-by-period editing and smoothing of an F0 track. For normal speakers, the F0 tracking function usually worked well, but for some participants with CP having poor voice quality F0 contours required extensive manual editing.

A total of 1600 contours (4 tones × 2 words × 5 repetitions × 40 speakers) were analysed. Across-speaker variation (and to a lesser extent, within-speaker variation) in vowel duration complicated a between-groups, graphical comparison of the F0 contours, so the duration of each utterance was normalized by plotting F0 values as a function of percentage time. The time normalization was accomplished with a linear interpolation algorithm in which each point along the F0 tone contour was transformed to a 200-point series.

For each individual contour, five acoustic measures were obtained from the original (pre-normalized) F0 data, including mean F0, maximum F0, minimum F0, F0 onset, and vowel duration. Mean F0 was defined as the average of all F0 values (i.e., at 2 ms intervals) along the F0 contour computed by Cspeech (and edited and corrected, if necessary). F0 onset was defined as the average of the first 10 ms of the F0 contour. Maximum F0 was the average of the three greatest F0 values along a contour, whereas minimum F0 was the average of the three lowest F0 values along a contour. Maximum and minimum F0 were measured to obtain a derived measure, F0 range, defined as the difference between the maximum and minimum F0 values. Vowel duration was measured as the interval between the first and last full glottal pulses of the vowel (Klatt, 1976). Finally, F0 slope was defined for Tone 3 and Tone 4 as the F0 range divided by the duration (in ms) of the tone contour.

Mean F0 contours

F0 plots, summary data, and statistical analyses were separated by gender due to the expected differences in mean F0. Figure 4 shows the original (pre-normalized) F0 tone
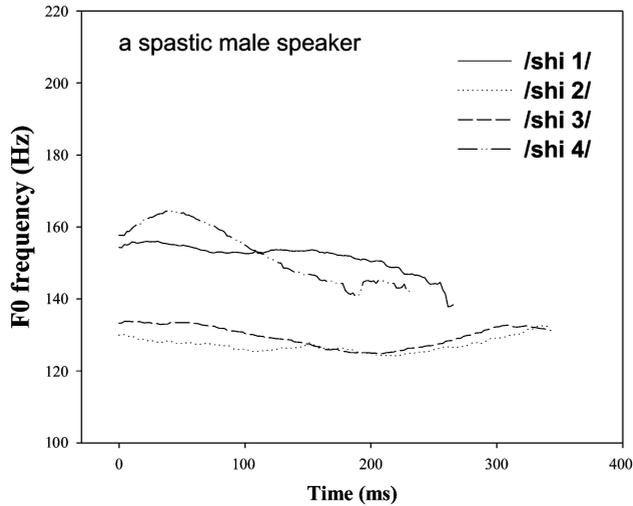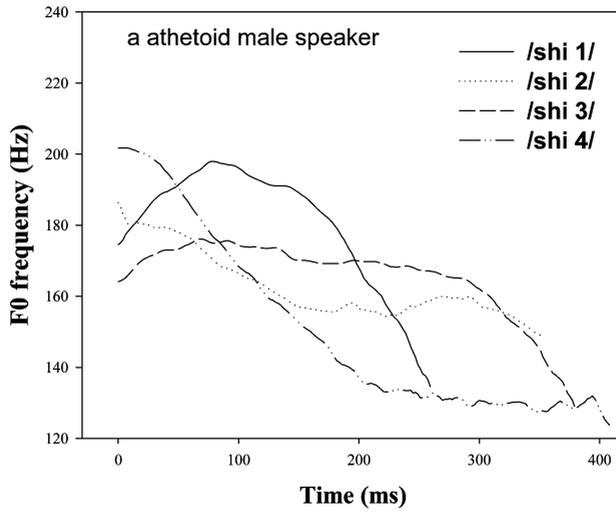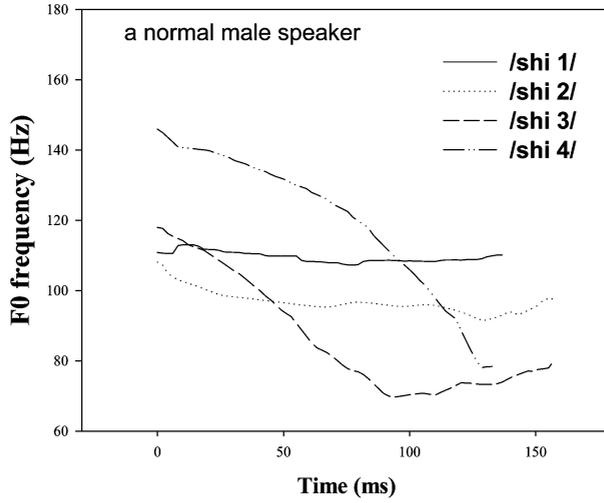
contours for the syllable /ʃi/ produced by a male control speaker (top), a male participant with a diagnosis of the athetoid form of CP (middle), and a male participant with a diagnosis of the spastic form of CP (bottom). The F0 contours produced by the control speaker (Figure 4, top) are fairly consistent with the pitch prototypes for the four tones (Figure 1), with the exception of the contour for Tone 2 which does not show a clear F0 rise. F0 contours for the speakers with athetosis (Figure 4, middle) and spasticity (Figure 4, bottom) are clearly not consistent with the pitch prototypes in Figure 4, with the possible exception of Tone 4 produced by the speaker with athetosis.

Examples of averaged and normalized F0 contours are shown in Figure 5. The top, middle, and bottom panels show data from the five males in the control, athetoid, and spastic groups, respectively. The group-averaged and normalized contours for the control speakers (Figure 5, top) are in line with the prototypes shown in Figure 1 and described by Chao (1948), except perhaps for the Tone 3 contour which turns up only minimally after the initial lowering. Note, however, that the F0 onsets of the averaged, normalized Tones 3 and 4 produced by the control speakers are separated exactly as expected from the corresponding prototypes in Figure 1. The group, normalized contours for the female control speakers were also consistent with the expected prototypes. The group, normalized tone contours for the male participants with athetosis show a lack of differentiation between the contours, especially for Tone 2 and 3. There is also a clear loss of contrast between Tones 2 and 3, and between Tones 1 and 4, for the speakers with spasticity (Figure 5, bottom panel). Similar loss of tone contour contrast was seen in the group patterns for the other participants with CP, although the patterns for the participants in the athetoid groups were perhaps most different from the patterns for the control speakers. In these group, normalized plots, a lack of differentiation between F0 contours for the four tones may reflect a true loss of contrast, but could also reflect large inter- and intra-speaker variability in F0 contour variability, even with a general retention of contour shape (the entire set of normalized contours are available upon request from the authors).

Parametric characteristics of F0 contours

Table II reports data, separated by gender, for three of the F0 variables (mean F0, F0 range and F0 onset) described in the Method.

Mean F0. The mean F0 data for the males and females in the control groups have the expected variation across tones, with the highest mean F0 for Tone 1 and the lowest mean F0 for Tone 3. Although mean F0 is affected by the relative complexities of the different contours, the similarity across tones of the male and female control data, even with their different F0 ranges, suggests the systematic nature of tone differentiation in production.

The groups of participants with CP all had higher mean F0 than the control groups, for all tones. For both males and females, the same general pattern emerged (with some minor exceptions), Tone 1 having the highest mean F0, followed by Tone 4, Tone 2, and Tone 3. In this sense, the general pattern of mean F0 across tones was essentially similar for the groups of participants with CP and the control groups. Clearly the mean F0 data were more variable for the groups of participants with CP, as compared to the control groups.

Figure 4. Original (pre-normalized) F0 tone contours for the syllable /ɕi/ produced by a male control speaker (top), a male participant with a diagnosis of the athetoid form of CP (middle), and a male participant with a diagnosis of the spastic form of CP (bottom). Note the different time scales for the participants with CP, as compared to controls.
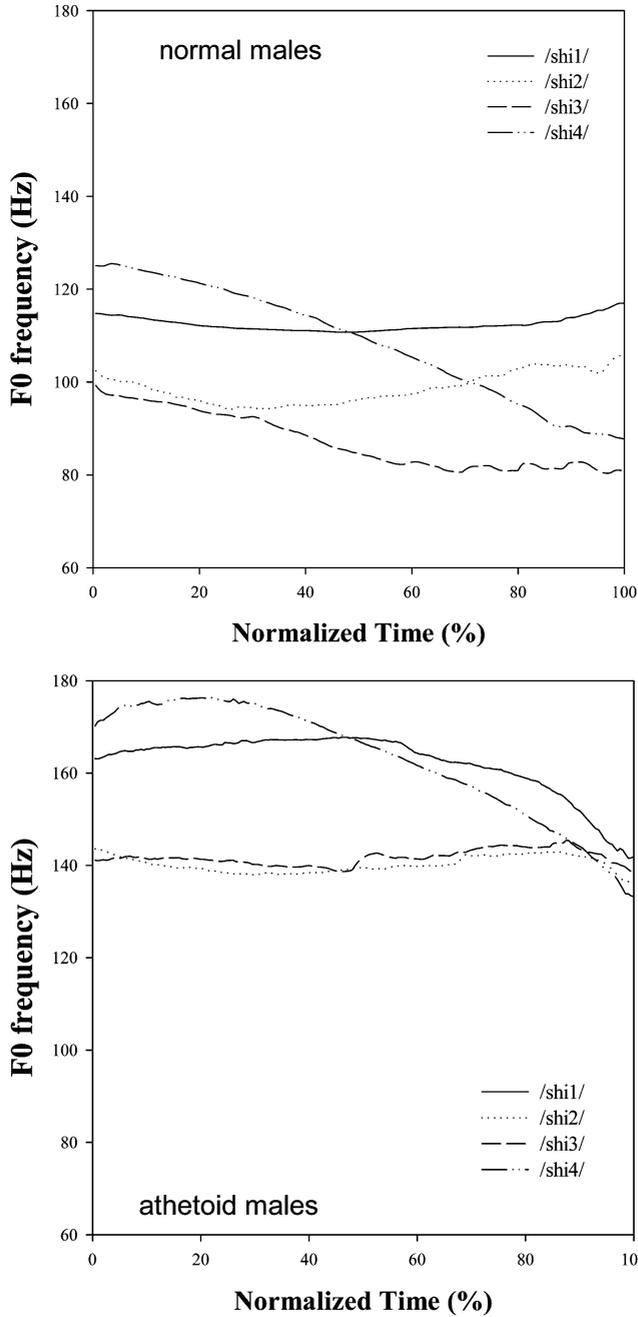
Figure 5. Mean, normalized tone contours of /ɕi1/, /ɕi2/, /ɕi3/, /ɕi4/ for the male control group (upper panel) and athetoid male group (lower panel).

In both male and female groups, two-way analysis of variance with group as the between-subject variable and tone as the within-subject variable (this model applies for all subsequent ANOVA results) showed significant effects for tone and group, with a significant interaction between the two factors only in the female group [Males: tone effect,

Table II. Means and standard deviations for mean F0, F0 range and F0 onset for the four groups. All values are in Hz.

	Athetoid			Spastic			Mixed			Normal		
	F0	range	OnsetF0	F0	range	OnsetF0	F0	range	OnsetF0	F0	range	OnsetF0
Male												
Tone 1	156	41	157	144	16	144	161	35	158	111	12	112
	(44)	(27)	(44)	(35)	(5)	(36)	(39)	(24)	(36)	(10)	(7)	(9)
Tone 2	141	32	142	134	27	135	139	35	140	97	23	100
	(21)	(19)	(22)	(34)	(14)	(33)	(37)	(32)	(38)	(11)	(14)	(10)
Tone 3	132	37	132	125	33	129	133	29	137	86	25	96
	(23)	(21)	(21)	(25)	(17)	(27)	(23)	(11)	(19)	(10)	(13)	(13)
Tone 4	153	50	165	146	43	160	151	54	162	106	38	122
	(33)	(29)	(39)	(41)	(20)	(41)	(39)	(25)	(40)	(11)	(18)	(17)
mean	146	40	149	137	30	142	146	38	149	100	25	108
Female												
Tone 1	275	53	281	258	32	265	233	29	238	215	33	220
	(45)	(36)	(51)	(54)	(14)	(58)	(30)	(16)	(32)	(23)	(13)	(20)
Tone 2	215	70	222	222	48	231	210	38	209	187	51	196
	(59)	(52)	(68)	(51)	(29)	(48)	(25)	(21)	(26)	(29)	(15)	(30)
Tone 3	221	66	233	218	54	232	196	39	200	130	86	169
	(46)	(40)	(41)	(60)	(46)	(65)	(34)	(22)	(32)	(29)	(36)	(39)
Tone 4	240	127	296	238	95	276	234	79	266	187	108	231
	(61)	(64)	(60)	(56)	(46)	(65)	(24)	(29)	(34)	(26)	(49)	(32)
mean	238	79	258	234	57	251	218	46	228	180	70	204

$F(3, 724)=49.56$, $p<.000$, $\eta^2=.17$; group effect, $F(3, 16)=4.41$, $p<.019$, $\eta^2=.453$; tone × group, $F(9, 724)=.574$, $p>.05$; Females: tone effect, $F(3, 731)=.874$, $p<.000$, $\eta^2=.311$; group, $F(3, 16)=3.11$, $p=.056$, $\eta^2=.368$, tone × group, $F(9, 731)=8.908$, $p<.000$, $\eta^2=.099$]. Post hoc Scheffé tests showed significant differences among all pairwise tone comparisons ($p<.05$), except for Tone 1 vs. Tone 4 in the male group. For groups, post-hoc Scheffé tests showed significant differences among all pairwise comparisons ($p<.05$), except for the comparison between males with athetosis versus a mixed diagnosis, and females with athetosis versus spasticity. The group effects had larger effect sizes than the tone effects, but even the smallest of these effect sizes (for tones in the male group, $\eta^2=.17$) seems worthy of interpretation.

F0 range. In the control groups, Tone 4 (falling tone) had the greatest F0 range, and Tone 1 (level tone) the smallest F0 range. As in the case of the control group, Tone 4 had the greatest range for each of the three groups of participants with CP, in both genders, but among the male participants with CP Tone 1 had relatively large ranges, especially when the participants with athetosis were compared to the control participants. The analysis of variance showed significant effects for tone and the tone × group interaction [Males, tone effect: $F(3, 724)=56.90$, $p<.05$, $p<.0001$, $\eta^2=.191$; tone × group: $F(9, 724)=4.73$, $p<.05$, $p<.0001$, $\eta^2=.056$; Females, tone effect: $F(3, 731)=146.76$, $p<.0001$, $\eta^2=.376$; tone × group: $F(9, 731)=3.71$, $p<.0001$, $\eta^2=.044$]. A group effect was significant only for females [$F(3, 16)=4.05$, $p=.026$, $\eta^2=.431$].

Post-hoc Scheffé tests showed significant range differences among all pairwise tone comparisons ($p<.05$) produced by males, except for Tone 1 vs. Tone 2 and Tone 2 vs. Tone 3; all pairwise tone comparisons for range were significant for the female participants. For the female group effect, post-hoc Scheffé tests showed significant differences among all

pairwise comparisons (p<.05), except for the comparison of control participants and participants with athetosis.

F0 onset. Expectations from the tone prototypes shown in Figure 1 and the averaged F0 contours shown for male and female control participants in the present study (Figure 5) would be for Tones 1 and 4 to have relatively high F0 onsets, Tone 3 to have the lowest F0 onset, and Tone 2 to have F0 onset between that of Tone 3 and Tones 1 and 4. This pattern was observed for the participants in all three CP groups, with minor reversals of the F0 onset values for Tones 2 and 3 produced by the female participants with athetosis and spasticity.

For males, analysis of variance for F0 onset data showed significant effects for tone and group [tone: $F(3, 724)=69.93$, $p<.0001$, $\eta^2=.496$; group: $F(3, 16)=3.53$, $p=.039$, $\eta^2=.399$]. The interaction between tone and group was not significant ($F(9, 724)=.51$, $p>.05$), consistent with the observation that the pattern of F0 onset across tones was the same for all groups of male participants. Post-hoc Scheffé tests showed significant onset differences among all pairwise combinations of the four tone contrasts, except between Tone 3 and Tone 2. The significant group effect in many ways mirrors the significant group effect described above for mean F0, wherein the participants with CP tended to have significantly higher mean F0s, as compared to the control group. For females, significant effects were found for tone and the interaction between tone and group [tone: $F(3, 731)=132.65$, $p<.0001$, $\eta^2=.47$; tone × group interaction: $F(9, 731)=3.28$, $p=.001$, $\eta^2=.039$]. The group effect was not significant [$F(3, 16)=2.43$, $p=.10$]. Post-hoc Scheffé tests showed that Tone 4 had a significantly higher F0 onset than Tones 2 and 3 ($p<.05$), but not Tone 1; the difference between Tones 2 and 3 was not significant.

Vowel duration. The means and standard deviation of vowel duration for the four groups are reported in Table III. Because there was no significant duration difference between males and females [$F(1, 38)=.14$, $p>.05$], further descriptive and statistical analysis was pooled across gender. The vowel durations for the participants with CP were longer than those for the control group, with much more extensive inter-speaker variability in each of the former groups. Analysis of variance showed significant effects for group and tone, as well as the group × tone interaction [group: $F(3, 16)=13.36$, $p<.0001$, $\eta^2=.715$; tone: $F(3, 1487)=28.17$, $p<.0001$, $\eta^2=.054$; group × tone: $F(9, 1487)=2.76$, $p=.003$, $\eta^2=.016$, respectively]. The very weak effect size for the interaction suggests that the pattern of tone-type duration differences across groups differed more by degree than kind. Post-hoc Scheffé tests showed significant differences between the control group and each of the participant groups with CP, but not between any of the latter groups. Post-hoc Scheffé tests for tone showed that Tone 4 had the shortest duration, and Tone 2 had the longest

Table III. Means and standard deviations for vowel duration for the four groups and four tones. All values are in msec.

	Athetoid	Spastic	Mixed	Normal
Tone 1	363 (147)	343 (122)	376 (157)	224 (79)
Tone 2	410 (205)	374 (118)	412 (195)	238 (67)
Tone 3	397 (173)	376 (132)	384 (150)	155 (69)
Tone 4	293 (130)	310 (95)	327 (224)	154 (57)

duration (p<.05).There was no significant difference between Tone 1 and Tone 3 (p>.05).

F0 slope for Tones 3 and 4. Among the four tones, the F0 contours associated with Tones 3 and 4 would be expected to have greater slopes than the contours for Tones 1 and 2 (see Figure 1). Slopes (in units of Hz/ms) for Tones 3 and 4 are reported for the four groups in Table IV. The control speakers had greater slopes as compared to the participants with CP speakers, for both genders; the slope difference between females and males is to be expected as a result of the gender-based difference in mean F0 range. For all groups, Tone 4 had a greater slope than Tone 3, and in the female groups of participants with CP this slope difference was particularly dramatic. The source of this difference appears to be the disproportionate F0 range difference between Tones 3 and 4 for the female participants with CP (see Table II), rather than a dramatic difference in vowel duration between these two tones.

For both genders, analysis of variance showed significant effects for tone and group, as well as a significant tone × group interaction for female participants [Males, tone: $F(1, 349)=53.68$, $p<.0001$, $\eta^2=.133$; group: $F (3, 16)=4.09$, $p=.025$, $\eta^2=.434$; Females, tone: $F(1, 358)=77.68$, $p<.0001$, $\eta^2=.178$; group: $F (3, 16)=4.60$, $p=.017$, $\eta^2=.463$; tone × group: $F(3, 358)=5.572$, $p=.001$, $\eta^2=.045$]. The tone effect derives from the greater slope for Tone 4, as compared to Tone 3, and the group effect is in the smaller slopes for the participants with CP, as compared to the control participants. The significant interaction for the female participants reflects the disproportionate differences between the F0 slopes for Tones 3 and 4 among the participants with CP, as compared to the control participants. However, similar to some of the other significant interactions reported above, the effect size associated with this interaction was quite small. For both male and females, post-hoc Scheffé tests for the group effect showed significant differences among all pairwise comparisons, except for the spastic male vs. mixed male group.

Discussion

Tone effects: Intelligibility and F0

The present study demonstrates that tone intelligibility in Mandarin is significantly affected in speakers with CP of the athetoid type, as compared to control speakers. Whereas tone intelligibility in speakers with the spastic and mixed forms of CP was lower than the control scores, the differences were not significant according to the conservative post-hoc test employed in the current analysis. Moreover, the tone intellgibility differences among the different groups of speakers with CP also failed to reach significance under the present analysis. It is possible that a more lenient post-hoc approach may have revealed additional significant differences.

Table IV. Mean F0 slopes and standard deviations for Tone 3 and Tone 4, reported for the four groups. All values are in Hz/msec.

	Athetoid	Spastic	Mixed	Normal
Male Tone 3	.13 (.14)	.11 (.08)	.08 (.05)	.21 (.11)
Male Tone 4	.13 (.11)	.15 (.06)	.15 (.10)	.31 (.16)
Female Tone 3	.19 (.12)	.16 (.14)	.15 (.18)	.58 (.37)
Female Tone 4	.55 (.43)	.32 (.20)	.56 (.47)	.69 (.41)

Another explanation for the lack of statistically-significant post-hoc results for the spastic-control and mixed-control comparisons, even with what appear to relatively large group deficits (12% for spastic, 17% for mixed), is the relatively low overall tone intelligibility (91%) for the control speakers. A large number of identification errors on Tones 2 and 3 for the control speakers reduced their overall tone intelligibility. It is difficult to know if the overall tone intelligibility for the control speakers is an accurate estimate of the true value, is a partial result of the testing format (open-set responses, which typically depress intelligibility scores relative to closed-set tests), or reflects something about the peculiarity of Tone 3 in Mandarin. However, the roughly 90% tone intelligibility for normal speakers may be a good estimate because Tones 2 and 3 are known to be highly confusable even when produced by normal speakers (Wang et al., 1999). Thus a 10% error rate for the intelligibility of normal tone production in Mandarin may be reasonable. Unfortunately, other studies that have investigated tone intelligibility in speakers with CP (e.g., Whitehill & Ciocca, 2000b) have not included a neurologically-normal control group, and so offer no point of comparison for the current finding.

In certain ways the current findings are consistent with those of Whitehill and Ciocca (2000b), who also reported tone intelligibility deficits in their sample of Cantonese-speaking participants with CP. The overall tone intelligibility of 73% in the present study is, however, approximately 15% lower than the overall tone intelligibility derived from Whitehill and Ciocca's Table 1 (2000b: 118). Because both studies obtained tone intelligibility data from single word productions, the differences in overall tone intelligibility may be explained by several different factors, including the different tone systems in Cantonese and Mandarin, different participant severities between the two studies, or some combination of the former and latter. There does appear to be a fairly sizable difference in speech severity across the two studies, with mean word intelligibility for the current speakers with CP of 34%, compared to 51% in Whitehill and Ciocca (2000b). This difference in overall word intelligibility is quite similar in magnitude to the across-study tone intelligibility difference of 15%, described above.

The tone intelligibility deficits among the current group of speakers with CP tended to be correlated with deficits in word and sentence intelligibility. Levels of tone intelligibility were very similar to vowel intelligibility but clearly higher than consonant, word, or sentence intelligibility. A similar pattern can be extrapolated from data reported for the Cantonese speakers with CP studied by Whitehill and Ciocca (2000b; see their Table 1, p. 118). Tone intelligibility in Mandarin and Cantonese could be more resistant to disruption by neurological disease than consonants, for example, because there are fewer tone distinctions than consonant distinctions in both languages. According to this view, speakers have more latitude in making production errors before violating the contrast space needed by listeners to make the necessary perceptual distinctions. The finding of similar intelligibility among the speakers with CP for tones and vowels, reported above, introduces a problem for this interpretation because in the current investigation the four tones were equivalent in intelligibility to vowels which were drawn from an inventory that had many more contrasts (Jeng, 2000). Alternately, perhaps tonal contrasts which are primarily under F0 control are easier to implement for speakers with CP, as compared to consonant contrasts. It would be interesting to address this question by devising some form of acoustic metric that would allow a comparative analysis between the acoustic phonetics of consonant and F0 production by persons with CP.

The current findings are also consistent with those of Whitehill and Ciocca (2000b) in showing varying tone intelligibility as a function of tone type. Direct comparisons between

the two studies are difficult because of the different tone systems in Cantonese and Mandarin, but in the present study there were clear differences between the relatively poor intelligibility of Tones 2 and 3 (see Wang et al., 1999), as compared to the better intelligibility of Tones 1 and 4. Moreover, there were many confusions between Tones 2 and 3, and in the groups of participants with CP, more frequent Tone 2-for-Tone 3 confusions than the reverse. Tones 2 and 3 share a relatively low F0 onset, as compared to the high F0 onset of Tones 1 and 4, and both Tones 2 and 3 have F0 contours that may include a rising portion, although Tone 3 seems to have been frequently produced in a reduced form, with a deletion or reduction of the final rising portion.

The F0 analysis of tones was undertaken for two reasons, to generate a basic description of F0 contours for tones in control speakers and in speakers with CP, and to gain some understanding of the acoustic basis of tone identification errors and tone confusions. The primary analysis of F0 contours was performed parametrically, with selected measurements of F0 mean, onset, and range, as well as F0 slope; vowel duration, assumed to be roughly the same as F0 contour duration, was also measured. The F0 data for control speakers agree roughly with data reported by Tseng (1990), Ho (1976), and Howie (1976), but the F0 onset for Tones 2 and 3 was slightly higher in the present study. However, because there were limited subjects in the previous studies (only one female in Tseng (1990), two in Howie (1974) and five in Ho (1976)), these differences may just reflect sampling issues. The current F0 data from control speakers, both qualitative (Figure 5) and parametric, are consistent with the tone prototypes set out in Figure 1, with the Tone 3 exception noted above.

The F0 data suggest that speakers with CP had substantial difficulty producing the prototype tone contour for Tone 3. This tone was typically produced with a relatively high F0, long duration, and was sometimes flat (based on examination of raw and averaged, normalized traces) or occasionally produced with a rising F0 at the end of the contour. The F0 onset for Tones 2 and 3 was quite similar in speakers with CP, and if the latter tone lacked a clear and relatively rapid falling portion, it is easy to see why it was heard so often as Tone 2. Moreover, examination of the individual F0 contours suggested that many speakers with CP, when intending to produce Tone 3, could not lower their F0 below their (already elevated) mean F0, resulting in a contour that had a relatively low F0 but not the more complex shape associated with Tone 3. The combination of the low F0 onset and a more simple contour than the prototype of Tone 3 may explain the greater number of Tone 2-for-Tone 3 confusions as compared to Tone 3-for-Tone 2 confusions.

The less-frequent but relatively common perceptual errors on Tone 2, usually heard as Tone 3, may be related to the similar F0 onset and rising sections. The confusion matrices also showed that Tone 1 was a relatively frequent error for any of the other three tones. An outstanding feature of the F0 contours for Tones 3 and 4 was reduced slopes, relative to the F0 contours produced by the control speakers. It makes sense that a reduction in the speed of F0 change, especially for tones which depend on rapid pitch changes, would tend to result in some errors (i.e., confusion of Tone 1 for other tones) for which the tone was perceived to be relatively flat.

As stated in the Methods, the current F0 analysis was performed for a relatively small subset of the words used in the intelligibility test. The general agreement between the results of the F0 characteristics of tone production, and the perceptual patterns reviewed above of tone confusion derived from the entire intelligibility test, would seem to support the claim that the tone production results from such a subset was representative of the behavior in general, at least for these kinds of words. The agreement is also consistent with

Ho's (1976) claim that tone patterns and their differentiation are not much affected by phonetic context or the identity of the vowel carrying the F0 pattern.

Interestingly, the parametric analysis of F0 contours, including F0 mean, onset, range, rate, and contour (vowel) duration, suggested that many of the patterns that differentiate the four Mandarin tones are more or less retained among speakers with CP. Compared to the control speakers, there is clearly more 'noise' in the F0 contours produced by speakers with CP, which would reduce the perceptual distinctiveness of the tones, but the overall impression from the F0 analysis is one of imprecision in production of tones, rather than qualitative disruption of tone distinctions. These observations are broadly consistent with the F0 analysis of tones produced by Cantonese speakers with CP, reported by Whitehill et al. (2000) and Ciocca et al. (2002). In these studies the level-tone or contour-tone F0 patterns tended to be more variable for the speakers with CP as compared to normal speakers, and showed more cross-tone overlap. Just as in the present study, however, the F0 contours did not show radical departures from the normal patterns. This latter finding may partially explain the relatively high tone intelligibility among the speakers with CP, as compared to aspects of their segmental (consonant) and word intelligibility. This observation is also consistent with the claims of Whitehill and Ciocca (2000a, b), as well as a study of phrase-level F0 contours in three adults with CP of the spastic type (van Doorn & Sheard, 2001) and a more recent analysis of statement vs. question F0 contours in severely-involved speakers with CP (Patel, 2002), that speakers with CP have speech production disorders that can be described as strictly phonetic (i.e., not phonological) in nature. It would be interesting to measure F0 contours for Mandarin and Cantonese tones in more connected speech materials, to see if this retention of tonal contrasts apparent in the current data and those of Whitehill et al. (2000) and Ciocca et al. (2002) holds for conversational speech samples as well.

The qualitative similarity of F0 tone contours produced by speakers with CP and control speakers also bears on the possible ''monotone'' nature of speech in persons with spastic dysarthria (Darley, Aronson, & Brown, 1975) and possibly other forms of neuromotor disorder associated with CP. The present F0 data do not suggest that monotone characteristics are typical of speakers with CP. Although speakers with CP often had F0 range and onset values that were significantly different from those of the control speakers, the contrasting *patterns* of these variables across the four tones were similar, albeit somewhat less differentiated, to those of the control speakers. Whereas the F0 contour contrasts between tones tended to be smaller for the speakers with CP, as compared with the control speakers, most of the speakers with CP still produced considerable, tone-related variation in their F0 contours, especially for Tone 4 (falling tone). Thus the decreased tone intelligibility of CP speakers does not seem to be related to a general monotonicity, at least at the syllable level. It will be interesting in future investigations to see how F0 contours associated with tone interact with sentence-level contours, such as those investigated by van Doorn and Sheard (2000) and Patel (2002). Traditionally, monotonicity has been defined at the phrase level, although it would certainly be expected that significant reductions in F0 variation at the phrase level would be reflected in reduction at the syllable level. A caveat here is that some aspects of tone-related F0 contours among CP speakers may be related to a stereotyped kind of physiological deficit that is particularly evident at the end of phrases. In the present study, speakers with athetosis seemed to produce falling F0 patterns at the end of tones, and falling F0 contours were very common in the Cantonese data reported by Whitehill et al. (2000) and Ciocca et al. (2002). Perhaps for some speakers with CP this reflects a stereotyped difficulty with

F0 control, especially when the syllable carrying the tone is in the utterance-final position where laryngeal muscular control and falling tracheal pressure have to be coordinated for proper influence on the vibratory rate of the vocal folds. This is another reason to determine for speakers with CP tone production and intelligibility characteristics in utterance positions that are not subject to the physiological conditions peculiar to utterance-final position.

Group effects on tone intelligibility and production

The tone intelligibility analysis showed that intelligibility increased across the athetoid, mixed, and spastic groups. The high occurrence of Tone 2-Tone 3 confusions was common to all three groups of speakers with CP, as was the asymmetry for these confusions, discussed above.

   Group effects for tone intelligibility or F0 contour production should be interpreted with some caution, because the significant group × tone interactions that were found, and would support the idea of differential tone intelligibility or production among different CP groups, were typically associated with very small effect sizes. With this caveat in mind, perhaps the special vulnerability of tone intelligibility among speakers with athetosis reflects the classic underlying neuropathophysiology of variable, uncontrolled tone in laryngeal muscles, with a resulting loss of precision in regulating F0. Alternatively, the general similarity of tone intelligibility and production in the current speakers with athetosis and spasticity may suggest that the classic neuropathophysiologies do not explain speech production symptoms in a simple way (see Neilson & O'Dwyer, 1984; Weismer, 2000). The weight of the evidence available to date, as reviewed in the Introduction, seems to point to dysarthria characteristics of speakers with athetosis and spasticity that are more alike than they are different. The F0 production data of Whitehill et al. (2000) and Ciocca et al. (2002) are consistent with this claim. One other possibility, of course, is that previous studies and the current one have not divided the groups properly or that clean differentiation of spastic from athetoid symptoms is not possible. Clearly, more work is required in this area to address the question of diagnosis of neuromotor disorder and its relation to dysarthria symptoms.

Summary

The present study demonstrates that tone intelligibility is a significant issue in speakers with CP, although perhaps not to the extent that consonant (and overall word) intelligibility is affected. The four tones of Mandarin are not equally unintelligible, but rather Tones 2 and 3 are more likely to be heard incorrectly as compared to Tones 1 and 4. There may be a slight tendency for the tone intelligibility deficit to be worse among speakers with the athetoid type of CP, than among persons with having primarily spastic, or mixed symptoms. The F0 contours underlying tone production reveal differences between the speakers with CP and controls, which are best described as differences in degree, not kind. The F0 contour analysis suggests that the most aberrant contours are produced when the tone shape is complex, and that tones that share certain F0 characteristics are most likely to be confused with each other. A logical extension of the current data would be to study the tone intelligibility and F0 contour characteristics of speakers with CP within different, sentence-level prosodic environments, especially for syllables in the non utterance-final position.

Acknowledgements

Notes

1. When Tone 3 is not in citation form, it is usually realized incompletely, lacking the rising tail.
2. Chang Hua Jen-Ai School for the Physically Handicapped (CHJAS) was founded in 1968. This is the first public boarding school for the physically handicapped in Taiwan. The majority of students at CHJAS have CP.
3. A phonetic symbol system, called Juin-Fuhau, is commonly used in Taiwan. The prototype of Juin-Fuhau was first introduced by the Ministry of Education of the Republic of China in 1913. It was intended as a pedagogical tool for teaching reading and standard Mandarin pronunciation. The symbols are based on Chinese calligraphic forms, and certain ones are derived directly from existing Chinese characters. The phonetic symbols may be printed alongside characters to indicate pronunciation and tone, a feature particularly useful in teaching Mandarin to native speakers in elementary schools. The listeners in this experiment therefore all had extensive training in this form of phonetic transcription, having been exposed to it from the onset of the primary education.
4. The word intelligibility described here was computed just for the consonant and vowel components of the syllable, and therefore was independent of the tone intelligibility.

References

Achilles, R. (1955). Communication anomalies of individuals with cerebral palsy: analysis of communication processes in 151 cases of cerebral palsy. *Cerebral Palsy Review*, *16*, 15–24.

Atkinson, J. E. (1978). Correlation analysis of the physiological factors controlling fundamental voice frequency. *Journal of Acoustical Society of America*, *63*, 211–222.

Chao, Y. R. (1948). *Mandarin Primer*. Cambridge, MA: Harvard University Press.

Ciocca, V., Whitehill, T. L., & Ng, S. S. (2002). Contour tone production by Cantonese speakers with cerebral palsy. *Journal of Medical Speech-Language Pathology*, *10*, 243–248.

Darley, F. L., Aronson, A. E., & Brown, J. R. (1975). *Motor speech disorders*. Philadelphia, PA: W. B. Saunders.

Erickson, D. (1993). Laryngeal muscle activity in connection with Thai tones. *Annual Bulletin, Research Institute of Logopedics and Phoniatrics*, *27*, 135–149.

Gay, T., Strome, M., Hirose, H., & Sawashima, M. (1972). Electromyography of intrinsic laryngeal muscles during phonation. *Annals of Otology, Rhinology and Laryngology*, *81*, 401–410.

Hallé, P. A. (1994). Evidence for tone-specific activity of the sternohyoid muscle in modern standard Chinese. *Language and Speech*, *37*, 103–123.

Hirano, M., Ohala, J., & Vennard, W. (1969). The function of laryngeal muscles in regulation fundamental frequency and intensity of phonation. *Journal of Speech and Hearing Research*, *12*, 616–628.

Hirose, H. (1997). Investigating the physiology of laryngeal structures. In W. J. Hardcastle, & J. Laver (Eds.), *The handbook of phonetic sciences* (pp. 116–136). Oxford: Blackwell.

Howie, J. I. (1974). On the domain of tone in Mandarin. *Phonetica*, *30*, 129–148.

Ho, A. T. (1976). The acoustic variation of Mandarin tones. *Phonetica*, *33*, 353–367.

Jeng, J.-Y. (2000). The speech intelligibility and acoustic characteristics of Mandarin speakers with cerebral palsy. PhD Dissertation, University of Wisconsin-Madison.

Klatt, D. H. (1976). Linguistic uses of segmental duration in English: Acoustic and perceptual evidence. *Journal of the Acoustical Society of America*, *59*, 1208–1221.

McDonald, E. (1987). Speech production problems. In E. McDonald (Ed.), *Treating Cerebral Palsy, for Clinicians by Clinicians*. Austin, TX: Pro-Ed.

Mecham, M. (1996). *Cerebral Palsy* (2nd edition). Austin, TX: Pro-Ed.

Milenkovic, P. (1996). *Cspeech Version 4 [computer Program]*. Madison, WI: University of Wisconsin Madison, Department of Electrical Engineering.

Neilson, P. D., & O'Dwyer, N. J. (1983). Reproducibility and variability of speech muscle activity in athetoid dysarthria of cerebral palsy. *Journal of Speech and Hearing Research*, *27*, 502–517.

Ong, S., & Yang, C.-H. (1997). On the energy and duration of the four tones of Mandarin speech. *Journal of Technique*, *12*, 125–129.

Patel, R. (2002). Prosodic control in severe dysarthria: preserved ability to mark the question-statement contrast. *Journal of Speech, Language, and Hearing Research*, *45*, 858–870.

Platt, L. J., Andrews, G., & Young, M. (1980a). Dysarthria of adult cerebral palsy: I. Intelligibility and articulatory impairment. *Journal of Speech and Hearing Research*, *23*, 28–40.

Platt, L. J., Andrews, G., & Howie, P. M. (1980b). Dysarthria of adult cerebral palsy: II. Phonemic analysis of articulation errors. *Journal of Speech and Hearing Research*, *23*, 41–55.

Tseng, C.-Y. (1990). *An Acoustic Phonetic Study on Tones in Mandarin Chinese.* Institute of History & Philology Academia Sinica, Special Publications No. 94. Taipei, Taiwan.

van Doorn, J. V., & Sheard, C. (2001). Fundamental frequency patterns in cerebral palsied speech. *Clinical Linguistics and Phonetics*, *15*, 585–601.

Wang, H. (1997). Speech intelligibility on the sentence level. Master's Thesis, Kaushung Normal University, Taiwan.

Wang, Y., Spence, M. M., Jongman, A., & Sereno, J. A. (1999). Training American listeners to perceive Mandarin tones. *Journal of the Acoustical Society of America*, *106*, 3649–3658.

Weismer, G. (2000). Review article: Murdoch, B. E. (ed.), 1998, Dysarthria: A physiological approach to assessment and treatment. *Clinical Linguistics and Phonetics*, *14*, 1–11.

Whalen, D. H., & Xu, Y. (1992). Information in Mandarin tones in the amplitude contour and in brief segments. *Phonetica*, *49*, 25–47.

Whitehill, T. L. (1997). Speech intelligibility in Cantonese speakers with congenital dysarthria. PhD dissertation, University of Hong Kong.

Whitehill, T., & Ciocca, V. (2000a). Perceptual-phonetic predictors of single-word intelligibility: A study of Cantonese dysarthria. *Journal of Speech, Language, and Hearing Research*, *43*, 1451–1465.

Whitehill, T., & Ciocca, V. (2000b). Speech errors in Cantonese-speaking adults with cerebral palsy. *Clinical Linguistics and Phonetics*, *14*, 111–130.

Whitehill, T. L., Ciocca, V., & Chow, D. T. Y. (2000). Acoustic analysis of lexical tone contrasts in dysarthria. *Journal of Medical Speech-Language Pathology*, *8*, 337–344.

Wolfe, W. (1950). A comprehensive evaluation of fifty cases of cerebral palsy. *Journal of Speech and Hearing Disorders*, *15*, 234–251.

Workinger, M. (1986). Acoustic analysis of the dysarthrias in children with athetoid and spastic cerebral palsy. PhD dissertation, University of Wisconsin-Madison.

Workinger, M., & Kent, R. D. (1991). Perceptual Analysis of the dysarthrias in children with athetoid and spastic cerebral palsy. In C. A. Moore, M. Kathryn, K. M. Yorkston, & R. D. Beukelman (Eds.), *Dysarthria and apraxia of speech : perspectives on management* (pp. 109–126). Baltimore, MD: Paul Brookes.