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Production of word-initial fricatives of Mandarin Chinese in prelingually deafened children with cochlear implants

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Abstract

Purpose: This study examined the production of fricatives by prelingually deafened Mandarin-speaking children with cochlear implants (CIs).
Method: Fourteen cochlear implant (CI) children (2.9–8.3 years old) and 60 age-matched normal-hearing (NH) children were recorded producing a list of 13 Mandarin words with four fricatives, /f, s, ɕ, ʂ/, occurring at the syllable-initial position evoked with a picture-naming task. Two phonetically-trained native Mandarin speakers transcribed the fricative productions. Acoustic analysis was conducted to examine acoustic measures including duration, normalised amplitude, spectral peak location and four spectral moments.
Result: The CI children showed much lower accuracy rates and more diverse error patterns on all four fricatives than their NH peers. Among these four fricatives, both CI and NH children showed the highest rate of mispronunciation of /s/. The acoustic results showed that the speech of the CI children differed from the NH children in spectral peak location, normalised amplitude, spectral mean and spectral skewness. In addition, the fricatives produced by the CI children showed less distinctive patterns of acoustic measures relative to the NH children.
Conclusion: In general, these results indicate that the CI children have not established distinct categories for the Mandarin fricatives in terms of the place of articulation.

Keywords: *Cochlear implants*, *children*, *Mandarin Chinese*, *fricatives*, *production*, *transcription*, *acoustics*

Introduction

Speech and language development in children with severe-to-profound hearing loss is compromised due to the deprivation of auditory input. Cochlear implants (CIs) stimulate the remaining auditory neural elements by directly converting the acoustic signals to electrical impulses, which provides important auditory sensation to users. With the language input and auditory feedback conveyed through this device, prelingually deafened children showed considerable improvement in their language and speech ability (e.g. Blamey, Barry, & Jacq, 2001; Geers, Tobey, Moog, & Brenner, 2008; Niparko, Tobey, Thal, Eisenberg, Wang, Quittner, et al., 2010; Ruffin, Kronenberger, Colson, Henning, & Pisoni, 2013; Spencer, Tye-Murray, & Tomblin, 1998; Tobey, Geers, Brenner, Altuna, & Gabbert, 2003; Tye-Murray, Spencer, & Woodworth, 1995). Recently, there is an increasing body of research on the development of consonants (production, perception or both) in children with CIs (Bouchard, Normand, & Cohen, 2007; Chin, 2002, 2003; Ertmer, Kloiber, Jung. Kirleis, & Bradford, 2012; Lin, & Peng, 2003; Liu, Zhou, Berger, Huang, & Xu, 2013; Serry & Blamey, 1999; Warner-Czyz, Davis, & Morrison, 2005; Warner-Czyz, Davis, & MacNeilage, 2010). In these studies, the investigators examined the accuracy rates of different categories of consonants produced by cochlear implant (CI) children and compared the acquisition order of CI children with the development path of normal-hearing (NH) children. In general, the findings revealed that, as a group, the CI children showed delayed acquisition of the consonant inventory but followed a similar order of consonant acquisition as the NH children.

Among different types of consonants, fricatives are of particular interest to the present study. Compared to other manners of articulation such as stops and glides, fricative articulation requires more precise motor control in forming the narrow

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constriction to the right size. This complexity may cause more difficulties in children with CIs than in NH children. In addition, previous studies have shown that, among different manners of articulation, fricatives are acquired at a relatively late age in normally-developing children (Dyson, 1988; Robb & Bleile, 1994; Stoel-Gammon, 1985, 2002) as well as in children with CIs (Flipsen, 2011; Serry & Blamey, 1999). While there have been a large number of studies on the perception and production of fricatives in NH children (Li, 2008; Morris, 2000; Nissen & Fox, 2005; Nittrouer, 2002; Nittrouer & Studdert-Kennedy, 1987), relatively few studies were conducted on the fricative production and perception in children with CIs (Bharadwaj, Tobey, Assmann, & Katz, 2005; Hedrick, Bahng, von Hapsburg, & Younger, 2011; Lane, Matthies, Guenther, Denny, Perkell, Stockmann, et al., 2007; Liu et al., 2013). Compared to NH children, CI children, as a group, demonstrate more difficulties in perceiving and discriminating fricatives (Summerfield, Nakisa, McCormick, Archbold, Gibbin, & O'Donoghue, 2002). This may be partially caused by the poor spectral resolution of the CI devices through which the 'place' features are transmitted (Tyler & Moore, 1992). In addition, certain fricatives such as /s/ and /f/ contain spectral energy concentration in a relatively high frequency region, which is out of the normal frequency limit of a typical CI. Although fricative perception is challenging to CI children, researchers found that CI children are likely to effectively use different acoustic cues in speech perception and show similar cue-weighting patterns as NH children (Giezen, Escudero, & Baker, 2010; Hedrick et al., 2011). For certain CI users (including both adults and children), CI devices provide sufficient acoustic information to successfully discriminate fricatives at different places of articulation (Munson, Donaldson, Allen, Collison, & Nelson, 2003; Summerfield et al., 2002).

Regarding the production of fricatives in CI users, two recent studies examined acoustic features of fricative production in English-speaking CI children. Uchanski and Geers (2003) compared the spectral moments (spectral mean, skewness and kurtosis) of two fricatives /s/-/ʃ/ between NH children and CI children. The CI children received cochlear implantation before 5 years of age and had an average of 5.5 years of experience with CIs. The results showed that the CI children generally followed the patterns of the NH children on the spectral features of these two fricatives. However, many CI children produced /s/ with the spectral mean as low as /ʃ/. This finding indicates that the CI children could not acoustically separate these two English fricatives in speech production.

More recently, Todd, Edwards and Litovsky (2011) expanded previous studies to examine the production of sibilant fricative contrast /s/-/ʃ/ in English-speaking children aged 4–9 years old who received a cochlear implant before 2.5 years of age. The fricative productions of the CI children and chronologically age-matched and hearing age-matched NH children were transcribed by trained native speakers and were used for acoustic analysis. The authors compared the results of transcription and acoustic analyses among the three groups of children. The results of transcription analysis showed that the CI children produced /s/ and /ʃ/ with lower accuracy than the NH children did. They also showed a different pattern of substitution from the NH children. In terms of the spectral analysis, the CI children showed less difference of spectral peak and spectral mean between /s/ and /ʃ/ than both groups of NH controls. These findings suggest that the CI children were less capable of producing /s/-/ʃ/ contrast than the NH children.

Compared to English, fricative production by CI children from other language backgrounds has not been extensively examined (Liker, Mildner, V., Šindija, 2007; Mildner & Liker, 2008; Peng, Weiss, Cheung, & Lin, 2004). Liker et al. (2007) examined the acoustic characteristics of fricatives produced by Croatian-speaking children with CIs at three time points over a 20-month period post-implantation. They found that the frequency range of /s/ and /ʃ/ showed considerable overlap in the CI children at all three time points, which indicates less differentiation between these two fricatives. In general, these studies have shown that CI children show delayed consonant acquisition and less separation of sibilant fricatives compared to age-matched NH children. So far, no studies have specifically examined the acoustic properties of fricative production in Mandarin-speaking children with CIs. The present study aims to further our understanding on the acoustic-phonetic characteristics of fricatives in Mandarin-speaking children with CIs. Of particular interest is to what extent the children with CIs can accurately produce the Mandarin fricatives and separate them in terms of the acoustic characteristics as age-matched NH children do.

Mandarin is a tonal language which also demonstrates a distinctive sound system from English. In terms of fricatives, Mandarin has five voiceless fricatives /f, s, ɕ, ʂ, x/ (f, s, x, sh, h in Pinyin). Compared to the two-way sibilant fricative contrast of /s/-/ʃ/ in English, Mandarin sibilant fricatives have a three-way contrast: alveolar /s/, alveolopalatal /ɕ/ and retroflex postalveolar /ʂ/. According to previous studies (Lee, Zhang, & Li, 2014, Wu & Lin, 1989), acoustic analyses of Mandarin fricatives produced by adult speakers have shown that /s/ has the highest frequency of the spectral peak and spectral mean, whereas /ʂ/ has the lowest. The frequency of the spectral peak and spectral mean of /ɕ/ is between /s/ and /ʂ/. With such a three-way distinction in

Mandarin, we can examine whether the greater number of contrasts would exacerbate the challenge of fricative production in Mandarin-speaking children with CIs.

The present study examined the production of Mandarin fricatives in 14 Mandarin-speaking CI children between 3–8 years of age. First, we compared the transcriptions of the CI children's fricative productions with those of NH age-matched children. The accuracy rates and error patterns of fricative productions in the CI children relative to those of the NH children are of interest to the present study. Based on previous findings on delayed consonant acquisition in CI children as opposed to NH children, we hypothesised that Mandarin-speaking children with CIs would also show lower accuracy in fricative productions compared to NH children. Second, we examined the acoustic properties of Mandarin fricatives produced by both CI and NH children. According to previous findings on consonant acquisition in normally-developing Mandarin-speaking children (Hua & Dodd, 2000; Li, 2008), we hypothesised that NH children, as a group, could make the place distinction in fricative production at this age range. In contrast, based on previous findings regarding less separation of /s/-/ʃ/ productions in English-speaking children with CIs, we hypothesised that Mandarin-speaking children with CIs would have more difficulty in acoustically differentiating Mandarin fricatives in speech production, due to the three-way contrasts in Mandarin fricatives.

Method

Participants

The present study recruited 14 prelingually deafened Mandarin-speaking children with CIs and 60 age-matched NH children. The CI children were aged 2.9–8.3 years at the time of recording. All of them were non-verbal prior to implantation and were reported to have no visual, developmental or cognitive problems except for a hearing impairment. After the surgery, all of the children received rehabilitation and basic speech and language services at professional rehabilitation centres in Beijing. Detailed demographic information of the CI children is shown in Table I. However, information related to the aetiology and the pre- and post-implantation thresholds for the CI children is not available. The NH children were between 3.1–9.0 years of age and all had a pure-tone average threshold at 500, 1000 and 2000 Hz of ≤20 dB HL. None of the NH children had been reported with language or speech impairments. All participants resided in the Beijing area. The parents of both groups of children spoke Mandarin at home and used Mandarin as their primary language of interaction in their daily life.

Table I. Demographic information of the 14 children with cochlear implants (CIs). The subjects were ordered based on their chronological age at recording.

Subject	Gender	Age at recording (years)	Age at implantation (years)	Length of device use (years)	CI device
1	M	2.91	2.60	0.31	N24R
2	M	2.93	1.16	1.77	Clarion CII
3	M	3.38	1.32	2.06	N24M
4	M	3.60	1.50	2.10	N24M
5	F	4.27	2.05	2.22	N24M
6	M	4.27	1.70	2.57	N24M
7	F	4.41	2.59	1.82	N24M
8	F	5.35	4.55	0.80	N24R
9	M	5.50	3.90	1.60	Clarion CII
10	F	5.51	3.10	2.41	N24M
11	F	6.53	5.56	0.97	N24R
12	F	7.53	5.19	2.34	Clarion CII
13	M	7.67	7.09	0.58	N24R
14	M	8.33	5.73	2.60	N24M

Materials and data collection

The speech material included 13 Mandarin words in which four target Mandarin fricatives /f, s, ɕ, ʂ/ (see Appendix for details) occurred at the initial position of each word. Considering the familiarity and picturability of these words to the young children, the vowel and tone environment were not controlled. The acoustic representation of Mandarin velar fricative /x/ is considerably influenced by the neighbour vowel. It was not used in the present study due to the lack of control on the vowel environment. Although the listed words were not phonemically and morphologically balanced, this is not of concern because all target fricatives occurred in the first syllable with no other preceding phonemes. In addition, since the acoustic analyses were based on the middle portion of the frication section, the impact of the following vowels on the target fricatives was limited. The inconsistent tone environment is not of concern either because lexical tone is carried by vowels. Although there is a consonant–tone interaction effect, it is mainly represented between voiced consonant and low tones (Bradshaw, 1999). Mandarin fricatives are all voiceless consonants. Therefore, the effect of lexical tone on the Mandarin fricatives was also limited. The target words were elicited through a picture-naming task. Pictures describing objects, cartoon characters or actions were presented on a computer screen. The experimenter asked the participants questions such as "what is this" or "what is he doing" to elicit the speech samples from each participant. Each participant produced the words one time. Note that some words were skipped or missing in some participants. Finally, there were 127 out of 182 tokens available in the CI children and 651 out of 780 tokens available in the NH children. All of the participants' speech samples were recorded in a quiet room through an ElectroVoice omnidirectional microphone (Model RE50B) to a Sony portable DAT recorder (Model TCD-D100) with a 44.1 kHz sampling rate.

Then, all recorded data was converted onto a computer hard disk at the same sampling rate of 44.1 kHz and 16-bit quantisation rate, which was then segmented into separate words and saved as individual wave files using CoolEdit 2000 (Syntrillium Software, Scottsdale, AZ).

Transcription

Both NH and CI children's fricative productions were transcribed by two native Mandarin speakers trained in phonetics. The words were fully randomised and presented one-by-one to the transcribers using a custom designed MATLAB program. The sound volume was adjusted to be at the most comfortable level. The transcribers were instructed to code the production of initial fricatives as accurate, acceptable but distorted or mispronounced. The mispronounced sounds were then transcribed into International Phonetic Alphabet (IPA) in a separate Excel worksheet. No limit was set on the number of playbacks and pauses were always allowed at any time. In addition, transcribers were not required to finish all stimuli on the same day.

Inter-transcriber reliability was calculated through a token-by-token comparison of the responses from these two transcribers and a Cohen's Kappa test. The two transcribers agreed on 93.5% of the total number of fricative productions pooled across the CI and NH children. In particular, the inter-transcriber agreement was 81.9% on the CI children's fricative productions and 95.6% on the NH children's fricative productions. The Cohen's Kappa test revealed a Kappa value of 0.777 with $p < 0.001$, which indicates substantial agreement between the two transcribers' coding.

Acoustic analysis

Seven acoustic measures were derived from acoustic analyses for each fricative segment: duration of frication, spectral peak location, normalised amplitude and four spectral moments (spectral mean, spectral variance, spectral skewness and spectral kurtosis). The landmarks of fricative onset and offset were used to determine the fricative duration. In particular, the onset and offset of the fricatives were estimated using a waveform and spectrographic display. Fricative onset was located at the point of the start of frication characterised by the presence of high frequency energy in the spectrogram. The offset was located at the point of cessation of frication or minimum intensity followed by the onset of vowel periodicity (Jongman, Wayland, & Wong, 2000; Nissen & Fox, 2005). Spectral peak was located at the highest amplitude on the spectrum that was derived from the fast Fourier transform (FFT) analysis in PRAAT software (Boersma & Weenink, 2016). In particular, the spectral slice was located at the midpoint of frication and a default 5-ms Gaussian window was used for the FFT. Normalised amplitude was calculated as the difference in dB between the root-mean-square (rms) amplitude of the entire portion of frication and the rms amplitude of the entire portion of the following vowel. The rms amplitude for both the fricative and the vowel were calculated using a custom MATLAB program. Specifically, it was calculated by squaring each value of a digital signal, finding the arithmetic mean of those squared values and then taking the square root of the result. This measure was used to normalize intensity across speakers. Spectral moments were measured using a custom MATLAB program on a 40-ms full Hamming window at the middle portion of frication. For the tokens with the frication duration less than 40-ms, a 20-ms Hamming window at the middle portion of frication was used.

Table II. Mean percentage scores by the two transcribers for accurate, acceptable and mispronounced productions of the four fricatives for children with normal hearing (NH) and cochlear implants (CIs).

		/f/	/s/	/ɕ/	/ʂ/
NH	accurate	100.0%	83.2%	88.1%	96.8%
	acceptable	0%	5.8%	9.6%	1.4%
	mispronounced	0%	11.0%	2.3%	1.8%
CI	accurate	48.1%	0%	37.5%	27.9%
	acceptable	13.0%	10.8%	22.5%	11.6%
	mispronounced	38.9%	89.2%	40.0%	60.5%

A mixed factor repeated measures ANOVA was conducted to examine the effect of group (between-subject factor) and place of articulation (within-subject factor) on these acoustic measures. Bonferroni correction was applied for the pair-wise comparisons of the within-subject factor. Prior to the statistical analysis, for a given acoustic measure, the mean value across different tokens was calculated for each fricative produced by each subject. In addition, due to the issue of unequal sample size across the places of articulation, the subjects with missing data in any fricatives were excluded from the ANOVA tests. As a result, data from 52 participants in the NH group and nine participants in the CI group were used for the ANOVA tests. By doing this, we ensured that all acoustic measures used for statistical analyses were from the same participants. Through applying these two procedures, the impacts of unequal sample size and the selection of stimuli on the acoustical and statistical analyses were greatly reduced.

Result

Transcription

Percentages of accurate, acceptable and mispronounced fricatives in both groups of children were calculated, and the mean percentage scores of the two transcribers are presented in Table II. Not surprisingly, the NH children produced all four

Table III. The error types, the number of tokens per error type and the percentage of each error type for individual fricatives in the children with normal hearing (NH) and cochlear implants (CIs). For both groups of children, the percentages were calculated by dividing the number of tokens per error type by the total number of token in each fricative.

	/f/	/s/	/ɕ/	/ʂ/
NH		/θ/,/ð/3 (1.9%) /ʂ/5 (3.2%) /f/2 (1.3%) affricate (/ts/) 4 (2.6%) stop 1 (0.6%) nasal 1 (0.6%)	/s/1 (0.9%) stop 1 (0.9%)	/s/1 (0.4%) /f/1 (0.4%) affricate (/tʂ/) 3 (1.2%)
CI	/x/4 (14.8%) /v/3 (11.1%) stops 3 (11.1%)	/x/3 (8.1%) /ɕ/4 (10.8%) /ç/4 (10.8%) /ð/1 (2.7%) /f/1 (2.7%) /ʂ/1 (2.7%) affricate (/tʂ/,/tʂ^h/,/tɕ/) 5 (13.5%) stops 9 (24.3%) glides 2 (5.4%) nasal 1 (2.7%) deletion 1 (2.7%)	/x/3 (15%) affricate (/tɕ/,/tɕ^h/) 4 (20%) glide 2 (10%)	/x/4 (9.3%) /ɕ/9 (20.9%) /f/2 (4.7%) affricate (/tʂ/,/tɕ^h/) 3 (7.0%) nasal 1 (2.3%) stops 6 (9.3%) glide 1 (2.3%) deletion 1 (2.3%)

^{h}The sound with this mark is aspirated sound.

fricatives with significantly higher accuracy rates than the CI children. In particular, the NH children produced the alveolar /s/ and the alveolopalatal /ɕ/ with lower accuracy rates than they did the labial-dental /f/ and retroflex postalveolar /ʂ/. For the CI children, both transcribers agreed that /f/ was produced with the highest accuracy rate, but /s/ was never produced as a typical alveolar fricative. In terms of the mispronounced fricatives, both NH and CI children showed the highest rate of mispronunciation for /s/.

For the mispronounced sounds, Table III summarises the substitution types and frequency of occurrence of each substitution type for each fricative in both NH and CI children. The judgement of the first transcriber was used when infrequent discrepancies occurred between the two transcribers. Comparison between the NH and CI children demonstrated that the CI children substituted the target fricatives with more diverse types of consonants. In contrast, the NH children usually used fricatives with different places of articulation or affricates with the same place of articulation in place of the target fricatives. Among the four fricatives produced by the CI children, /s/ and /ʂ/ were substituted with nearly the entire range of the consonant inventory. Based on the transcribers' description of sound quality, the CI children also showed a tendency to produce fricatives with the constriction point near the palatal region for most acceptable productions and some of the substituted sounds. For instance, the CI children substituted alveolar /s/ and retroflex postalveolar /ʂ/ with alveolopalatal /ɕ/. In addition, they also substituted alveolar fricative /s/ with palatal fricative /ç/, which does not occur in Mandarin Chinese. It is also noteworthy that, while the NH children switched between /s/ and /ʂ/ or /ɕ/, the CI children substituted /ʂ/ or /ɕ/ for /s/, but did not substitute /s/ for the other fricatives. Since no production of /s/ was perceived as accurate, these findings suggested that the alveolar fricative /s/ had not truly emerged in these CI children.

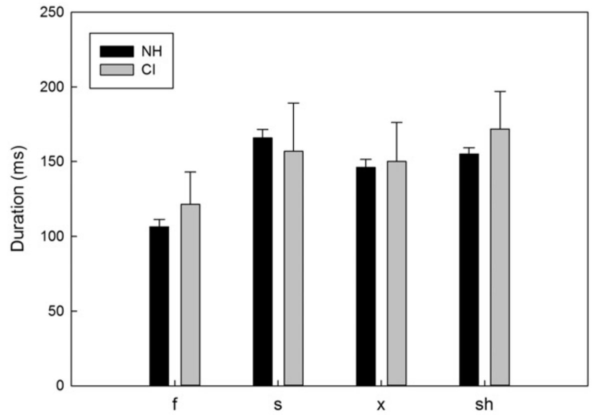

Figure 1. Means and standard errors of the duration of the four Mandarin fricatives in the children with normal hearing (NH) and cochlear implants (CIs). The IPA symbols for the four fricatives are /f, s, ɕ, ʂ/, respectively.

Consistent with our prediction, the NH children produced the four Mandarin fricatives with high accuracy, and the CI children produced all four Mandarin fricatives with much lower accuracy and more diverse error patterns. In addition, among the four fricatives produced by the CI children, the labiodental /f/ and alveolopalatal /ɕ/ showed higher accuracy and fewer substitution types than the alveolar /s/ and postalveolar /ʂ/.

Acoustic-phonetic features

Prior to the acoustic analysis, the productions perceived as stops, glides or nasals were excluded. Only the frication portion extracted from tokens perceived as fricatives or affricates were used for the following acoustic examination.

Fricative duration. Figure 1 shows the fricative durations in the NH and CI children. The NH

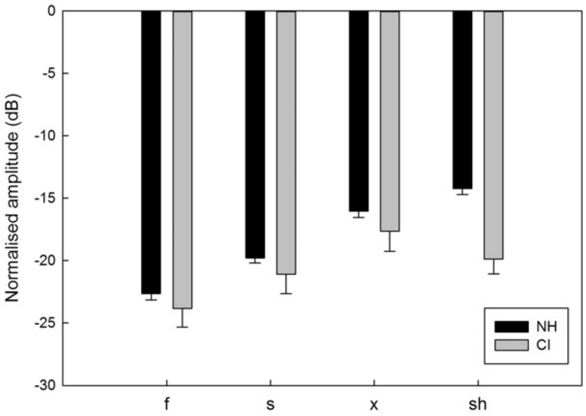

Figure 2. Means and standard errors of the normalised amplitude of four fricatives (/f, s, ɕ, ʂ/) in the children with normal hearing (NH) and cochlear implants (CIs). The normalised amplitude is the difference in dB between the rms amplitude of the fricative and that of the following vowel.

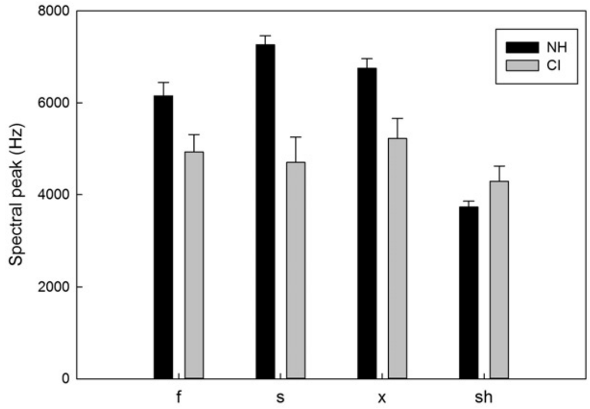

Figure 3. Means and standard errors of the spectral peak of four fricatives (/f, s, ɕ, ʂ/) in the children with normal hearing (NH) and cochlear implants (CIs).

children produced /s/ with the longest duration and /f/ with the shortest duration. The CI children showed a slightly different pattern from that of the NH children in that they produced /ʂ/ with the longest duration. Statistical analysis revealed a main effect of place of articulation ($F(3,177) = 14.48$, $p < 0.001$, $\eta_p^2 = 0.197$). Subsequent pair-wise comparison showed significantly shorter duration of /f/ than the other three fricatives. However, as a group, the CI children did not show significant differences from the NH children. No group-by-place interaction was found.

Normalised amplitude. Figure 2 shows the normalised amplitude which represents the difference in dB between the rms amplitude of the fricative and that of the following vowel. As expected, due to the relatively weak amplitude of non-sibilant fricative /f/ compared to sibilant fricatives /s, ɕ, ʂ/, the normalised amplitude of /f/ was lower than that of /s, ɕ, ʂ/ in both the NH and CI children. The ANOVA results revealed a significant main effect of place of articulation ($F(3,177) = 27.881$, $p < 0.001$, $\eta_p^2 = 0.321$). The pair-wise comparisons indicated that the normalised amplitude of /f/ was significantly lower than those of all other three fricatives. In addition, the normalised amplitude of /s/ was significantly lower than those of /ʂ/ and /ɕ/. The ANOVA results also revealed a main effect of group ($F(1,59) = 8.225$, $p = 0.006$, $\eta_p^2 = 0.122$). This demonstrated that the CI children produced lower normalised amplitude than the NH children. A significant interaction effect ($F(3,177) = 3.469$, $p = 0.017$, $\eta_p^2 = 0.056$) was also found, which indicates that the CI children showed a different pattern from the NH children on the normalised amplitude of the four Mandarin fricatives. In particular, the NH children showed a tendency of increased normalised amplitude as the articulation place moved further back (/ʂ/ > /ɕ/ > /s/ > /f/). The CI children did not follow this order in that the normalised amplitude of /ʂ/ was lower than that of /ɕ/.

Spectral peak location. Figure 3 demonstrates the spectral peak location of each fricative in the NH and CI children. In the NH children, /s/ had the highest frequency value of spectral peak and /ʂ/ had the lowest. These findings were consistent with the results of Lee et al. (2014). It is known that spectral peak represents the resonant feature of the front cavity formed by the fricative constriction. As the place of articulation moves back from /s/ to /ʂ/, the front resonant cavity becomes longer and the resonant frequency decreases. Regarding the peak location of /f/, previous acoustic analysis has shown that this Mandarin fricative has a relatively wide distribution of spectral energy and a relatively high spectral peak. These features were also observed in the present study. In general, the NH children showed a pattern of spectral peak location similar to that of Mandarin-speaking adults.

The spectral peak of the CI children showed a different pattern from that of the NH children. On one hand, the CI children showed lower spectral peaks for fricatives /f, s, ɕ/ than the NH children. On the other hand, the CI children showed less distinctive spectral peak locations across different places of articulation. The spectral peaks of all four Mandarin fricatives produced by the CI children were located at a similar mid-frequency region of 4000–5000 Hz. The similar spectral peak location of the CI children indicated that they may form similar articulatory gestures when they produce these Mandarin fricatives. The ANOVA results revealed a significant main effect of place of articulation ($F(3, 177) = 12.732$, $p < 0.001$, $\eta_p^2 = 0.177$). Subsequent pair-wise comparisons showed that the spectral peak of /ʂ/ was significantly lower than that of the other three fricatives. A main effect of group was also found ($F(1,59) = 15.198$, $p < 0.001$, $\eta_p^2 = 0.205$), which revealed a significantly lower spectral peak

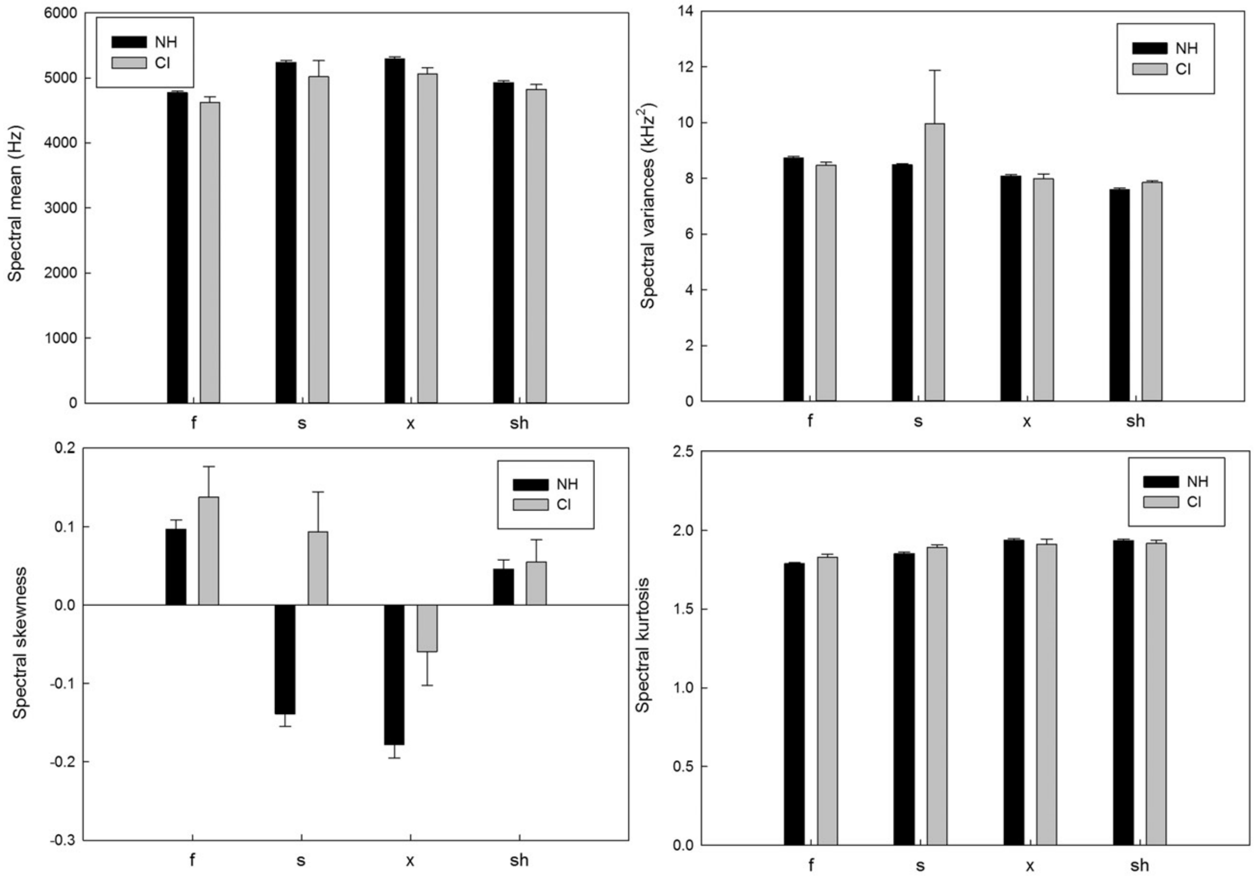

Figure 4. Means and standard errors of the four spectral moments of four fricatives (/f, s, ɕ, ʂ/) in the children with normal hearing (NH) and cochlear implants (CIs).

in the CI children than in the NH children. The different patterns of spectral peak on individual fricatives between the CI and NH children were demonstrated by a significant interaction effect of group by place of articulation ($F(3,177) = 6.139$, $p = 0.001$, $\eta_p^2 = 0.094$). Specifically, while the NH children showed a decreasing spectral peak frequency as a function of place for the three sibilants, the CI children did not follow this pattern. Instead, they showed a lower spectral peak frequency of /s/ relative to /ɕ/. This finding suggests that, in addition to an overall group difference, the NH and CI children implemented the place distinction in a different fashion.

Spectral moments. Figure 4 plots the mean values of spectral moments (spectral mean, variance, skewness and kurtosis) at the middle point of each fricative in both groups of children. The NH children produced /ɕ/ and /s/ with a high spectral mean and /f/ and /ʂ/ with a low spectral mean. The CI children generally demonstrated a pattern similar to the NH children on individual fricatives, but they produced a lower spectral mean than the NH children for all four Mandarin fricatives. The ANOVA results showed a significant main effect of group ($F(1,59) = 11.137$, $p = 0.001$, $\eta_p^2 = 0.159$) and main effect of place of articulation ($F(3,177) = 26.694$, $p < 0.001$, $\eta_p^2 = 0.312$). The pair-wise comparisons showed that the spectral mean of /ʂ/ was significantly lower than that of /s/ and /ɕ/ but significantly higher than that of /f/. No interaction effect between group and place of articulation was found.

For spectral variance, the ANOVA results revealed a significant main effect of place of articulation ($F(3, 177) = 10.966$, $p = 0.001$, $\eta_p^2 = 0.159$) and a significant interaction effect between group and place of articulation ($F(1,59) = 3.857$, $p = 0.047$, $\eta_p^2 = 0.061$). The pair-wise comparisons showed that all contrasts except /f/-/s/ were significantly different on the spectral variance. As a group, the CI children did not show significant differences when compared to the NH children. However, the significant interaction effect suggested that the CI children showed a different pattern from the NH children on this particular spectrum feature across the four places of articulation. It is noteworthy that the spectral variance of /s/ in the CI children was substantially greater than that in the NH children and the other fricatives with a considerably larger variation. This finding suggests that the distribution of spectral energy of /s/ in the CI children was less consistent across individual CI speakers.

For spectral skewness, the NH children showed high-frequency tilted spectra for the fricatives /s/

Table IV. Summary of pair-wise comparison tests on fricative place contrasts for each acoustic measure in the children with normal hearing (NH) and cochlear implants (CIs).

		/f/-/s/	/f/-/ʂ/	/f/-/ɕ/	/s/-/ʂ/	/s/-/ɕ/	/ʂ/-/ɕ/
NH	duration	*	*	*		*	
	spectral peak location	*	*		*		*
	normalised amplitude	*	*	*	*	*	*
	spectral mean	*	*		*		*
	spectral variance	*	*	*	*	*	*
	spectral skewness	*	*	*	*		*
	spectral kurtosis	*	*	*	*	*	
CI	duration						
	spectral peak location						
	normalised amplitude						
	spectral mean			*			*
	spectral variance		*				
	spectral skewness			*		*	*
	spectral kurtosis		*				

*Statistical significance ($p < 0.05$).

and /ɕ/ relative to /f/ and /ʂ/. This finding is consistent with that reported in Lee et al. (2014) for Mandarin-speaking adults. However, in the CI children, only one fricative /ɕ/ showed high-frequency tilted spectra. The magnitude of the spectral tilt was much less than with the NH children. In addition, the CI children showed an opposite direction of spectra tilt for the fricative /s/ from the NH children. The ANOVA revealed significant main effects of group ($F(1,59) = 16.906$, $p < 0.001$, $\eta_p^2 = 0.223$) and place of articulation ($F(1,59) = 37.176$, $p < 0.001$, $\eta_p^2 = 0.387$). The pair-wise comparison demonstrated that all six pairs of fricative contrasts were significantly different on their spectral skewness. In addition, a significant interaction effect ($F(1,59) = 8.969$, $p < 0.001$, $\eta_p^2 = 0.132$) was also found. This suggested that, in addition to the overall difference between the CI and NH children, these two groups also differed in specific pattern of skewness among the four places of articulation.

For spectral kurtosis, the ANOVA results only revealed a significant main effect of place of articulation ($F(1,59) = 26.460$, $p < 0.001$, $\eta_p^2 = 0.582$). Subsequent pair-wise comparisons revealed that all contrasts except /ʂ/-/ɕ/ were significantly different on the spectral kurtosis.

Summary of findings

In agreement with our prediction, the acoustic analysis showed that the NH children could better separate the Mandarin fricatives than the CI children in speech production. This finding was further confirmed through a one-way repeated measures ANOVA conducted on each of the acoustic measures for the CI and NH children, respectively. The results demonstrated a significant effect of place of articulation on all seven measures in the NH children, but only on normalised amplitude and spectral skewness in the CI children. The results of subsequent pair-wise comparison with Bonferroni correction are summarised in Table IV.

As shown for the NH children, the majority of the fricative contrasts showed significant differences for the seven acoustic measures. However, the CI children only demonstrated a few significantly different contrasts for the spectral moments. Note that the acoustic analyses were conducted on the data with the productions perceived as stops, glides or nasals removed. The lack of statistical differences among these four fricatives within the CI children as well as the significant differences between the CI and NH children on these acoustic measures indicate that these CI children had not established phonetic categories for these Mandarin fricatives as the NH children did.

In general, the comparison of the acoustic measures demonstrated that the CI children differed from the NH children in spectral peak location, normalised amplitude, spectral mean and spectral skewness. In addition to the overall group difference between the CI and NH children, significant interaction effects were noted for the measure of normalised amplitude, spectral peak location, spectral variance and spectral skewness. These results indicate that the CI children failed to establish acoustic categories for the Mandarin fricatives. Meanwhile, the fricative development in the CI children was delayed and did not match the pattern of the NH children.

Discussion

The aim of the present study is to examine the perceptual quality and acoustic characteristics of Mandarin fricatives produced by CI children in comparison to their age-matched NH peers. It was of particular interest to this study whether prelingually deafened children with less than 3 years of experience using cochlear implants can establish phonetic categories for fricative consonants. Productions of four Mandarin fricatives were perceived and transcribed by two phonetically trained native Mandarin-speaking listeners. In addition, acoustic analysis was conducted to compare the acoustic-phonetic features of fricative productions between the CI children and their NH peers.

When evaluating the perceptual quality of children's speech production, listeners usually make judgements from an articulatory perspective or a phonological perspective. The articulatory approach focuses on "the planning and execution of smooth sequences of highly overlapping gestures of the speech organs" (Fey, 1992, p. 225) and involves individual speech sounds. The output of articulatory movement can be viewed as a series of phonetic features that form individual speech sounds in a speech stream. According to the notion of distinctive feature development (Menyuk, 1968), children follow a certain order of acquisition for consonant features. When a speech sound involves all features that have been mastered by a child at a particular age, the speech sound will be perceived as accurate and will match the internal exemplar of the sound in the listener. On the contrary, if a speech sound involves certain features that are not manageable to a child at a particular age, the speech sound will be produced with deviant features or be substituted with another sound. The articulatory deviance indicates deficient or inaccurate speech motor control of the speaker. When examining the language acquisition, especially the acquisition of phonemes in a certain language, researchers need to take into account a broader view of the entire sound system. This, therefore, is related to the phonological approach. This approach focuses more on the pattern of speech sound organisation and involves the entire phoneme repertoire. From this perspective, when a speech sound is accurately produced by a certain proportion of children at a particular age across different pronunciation situations, it can be judged that this phoneme has been acquired. Usually, the specific criterion used to judge the acquisition of phoneme varies across different studies.

In the present study, the results of transcription analyses demonstrated that the CI children produced all four Mandarin fricatives poorly relative to the NH children's productions. None of the four fricatives reached 50% accuracy. The low accuracy score was also reported in Peng et al. (2004) in which the accuracy rate of the five Mandarin fricatives ranged from 28.33% for /s/ to 65.42% for /x/ in their CI children who had an average of 3.5 years of implant experience. Even when a broader criterion that considered acceptable productions as accurate was applied, the highest accuracy rate was only 62% for the labiodental fricative /f/. Templin (1957) suggested using 75% as the cut-off to determine whether a speech sound is mastered or not. This criterion has been widely used to examine the acquisition of speech sounds in normally-developing children. If the same criterion were used for the CI children's productions in the present study, none of the four fricatives would have been fully acquired. In a more recent study, Serry and Blamey (1999) suggested that 50% accuracy should be used to define "customary production" in CI children. Following this criterion, only two fricatives would barely reach this standard. Although these Mandarin fricatives were produced with an overall poor accuracy rate, not all of them were produced equally as poor. The fricatives /f/ and /ɕ/ showed higher accuracy rates and less diverse error types. Previous studies on the consonant development of normally developing Mandarin-speaking children reported that /f/ and /ɕ/ were acquired earlier than /s/ and /ʂ/ (Hua & Dodd, 2000; Li, 2008). Although the CI children in our study did not fully master these Mandarin fricatives, the transcription analyses showed a developmental pattern roughly similar to that of normally developing children.

Qualitative examination of the errors of the CI children's productions indicated that the CI children showed a diverse substitution pattern. They used fricatives with different places of articulation and consonants from other manners of articulation in place of the target fricatives. Some of the substituted sounds shared no phonetic feature with the target fricative. The cause of this confusion is unclear. We speculate that it might be associated with different implant insertion depth in different users. A previous study showed that NH listeners' consonant recognition was differentially affected by frequency shift that simulates the change of tonotopic distance along the basilar membrane of the cochlea (Zhou, Xu, & Lee, 2010). In particular, broad features of voicing, manner and place of articulation were all subject to frequency shift. Due to different insertion depths during cochlear implantation, the recipient's perception of consonant features may be distorted which, in turn, may affect their production of the consonants.

Note that, although the NH children produced all four Mandarin fricatives with a very high level of accuracy, they still showed more than 10% mispronunciation for the /s/ sounds. Further examination of the age range of these NH children who mispronounced /s/ showed that eight out of 13 children were younger than 5 years old and two of them were 7 years old. Based on the normative data of English-speaking children's consonant development and the reports on Mandarin-speaking children's phonological development, mispronunciation of /s/ is not rare in children of this age range (Hua & Dodd, 2000; Li, 2008). Therefore, the error patterns of the NH children were consistent with previous findings.

Quantitative acoustic analysis showed that the CI children had smaller differences in acoustic features across the four fricatives than the NH children (see Figures 2–4). These results suggest that the CI children were less likely to distinguish the places of articulation in their fricative production. The statistical analysis on each of the acoustic measures in each group of children (see Table IV) provided additional evidence of a reduced acoustic separation among these fricatives in the CI children relative to the NH children. The lack of acoustic separation in the CI children may be caused by insufficient cues to guide them to form appropriate and accurate articulation gestures. The under-developed speech motor control in CI children may also contribute to the inaccurate production of Mandarin fricatives. It is noteworthy that the CI children also demonstrated a greater variation for all acoustic measures than the NH children. This finding indicates large individual differences in speech production in the CI children.

The seven acoustic measures examined in the present study included both temporal and spectral aspects. Although the fricative durations did not show significant difference between the CI and NH children, a general trend of longer fricative duration in the CI group than the NH group can be found for most fricatives. This result was consistent with the finding of longer duration of speech sounds in hearing-impaired children and CI children in previous work (e.g. Pratt & Tye-Murray, 1997; Yang, Brown, Fox & Xu, 2015). Among the six spectral parameters, spectral variance successfully distinguished all fricative contrasts in the NH children. This result was consistent with the findings in Jongman et al. (2000) and Nissen and Fox (2005). In the present study, normalised amplitude was also found to effectively separate all fricative contrasts, which has not been reported in previous studies and was inconsistent with Lee et al. (2014), who examined Mandarin-speaking adults. Future studies with a greater sample size of children at different age groups are needed to examine how this acoustic measure can be used to distinguish fricative contrasts in children vs adults. Jongman et al. (2000) and Nittrouer (1995) found that the acoustic measures of spectral peak, spectral mean, skewness and kurtosis characterise the place of articulation. Therefore, the acoustic measures adopted in the present study composed a complete acoustic profile for fricative production. However, in the CI children, none of the fricative contrasts can be effectively separated by these acoustic measures. This result indicates that the fricative productions of the CI children were not separable and did not match the target fricatives that they attempted.

Uchanski and Geers (2003) found that English-speaking CI children reached or approximated the normal values produced by age-matched NH children. However, our transcription and acoustic analyses of the fricative productions from 14 Mandarin-speaking CI children demonstrated that these CI children actually had not acquired the Mandarin fricatives and differed from the age-matched NH children in the manner of fricative production. Our finding was similar to that in Todd et al. (2011), who found that English-speaking CI children produced less contrast between /s/ and /ʃ/ compared to chronological age-matched and hearing-age-matched children. Of course, when we compare our results with other studies on CI children's speech production, we need to take into account the heterogeneity of participants. The participants in Uchanski and Geers (2003) had an average of 5 years of implant usage. The CI children in the present study were non-verbal prior to surgery and all received implants younger than 7 years of age. In addition, they had a relatively short period of experience with the device (<3 years). Lack of separation of the Mandarin fricative categories in these CI children is to be expected considering the consonant development of NH peers, less language input the CI children received and the relatively poor perceptual ability of fricatives in the CI children associated with the limitation of the device.

Although informative, the findings of the present study were based on a small size of samples. In addition, due to the heterogeneity of CI history in our participants, it is not feasible to evaluate how the factors of age at implantation or length of device use affect fricative production in such a small number of subjects. To better examine the potential factors that contribute to the development of speech segments in CI children, a larger sample size is required. A better designed speech material with the vowel environment controlled and token number balanced is also needed. Other than the cross-sectional study comparing the fricative production between CI and NH children, a longitudinal design to examine the acoustic development of different types of consonants in CI children relative to chronological age matched and hearing age matched normal developing children will also be a focus for the future studies. Such studies will bear strong clinical implications in habilitation of prelingually deafened, Mandarin-speaking children with cochlear implants and also benefit the clinical practice of speech production in prelingually deafened children from other language backgrounds.

Conclusion

The present study investigated the fricative production in Mandarin-speaking CI children relative to chronological age matched NH children. On the basis of adult listeners' judgements of the CI children's speech samples and the comprehensive acoustic analysis of their fricative production, the results suggest that the CI children demonstrated an overall significantly poor ability in producing Mandarin fricatives. Specifically, the CI children failed to establish separate acoustic categories for the Mandarin fricatives. Among different places of articulation, the CI children performed better on the labio-dental /f/ than the alveolar /s/ and the alveolopalatal /ɕ/, which generally follow a trajectory of acoustic development similar to normal developing children. These findings furthered our understanding in the speech production of young children with CIs and provided new insight in evaluating the speech development, especially consonant production, in non-English-speaking children with CIs. The data reported in this study also bears important clinical implications in that it helps clinicians recognise the pattern of consonant development in CI children from which clinicians can design more habilitation activities to address the late developed and more complex speech sounds in practice.

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Appendix

The word list used to collect speech samples from the children with normal hearing (NH) and cochlear implants (CIs).

Fricative	Pinyin	English gloss
/f/	**f**ang feng zheng	kiteflying
	fang zi	house
	fei ji	airplane
/s/	**s**un wu kong	Monkey King
	san	three
	si	four
/ɕ/	**x**ie zi	write
	xi zao	bathe
/ʂ/	**sh**a yu	shark
	she tou	tongue
	shi zi	lion
	shou qiang	handgun
	shu	tree

Note: the bold fonts in pinyin represent the fricatives of interest.