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Acoustic properties of vocal singing in prelingually-deafened children with cochlear implants or hearing aids

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ABSTRACTS

Objective: The purpose of the present study was to investigate vocal singing performance of hearing-impaired children with cochlear implants (CI) and hearing aids (HA) as well as to evaluate the relationship between demographic factors of those hearing-impaired children and their singing ability.
Methods: Thirty-seven prelingually-deafened children with CIs and 31 prelingually-deafened children with HAs, and 37 normal-hearing (NH) children participated in the study. The fundamental frequencies (*F*0) of each note in the recorded songs were extracted and the duration of each sung note was measured. Five metrics were used to evaluate the pitch-related and rhythm-based aspects of singing accuracy.
Results: Children with CIs and HAs showed significantly poorer performance in either the pitch-based assessments or the rhythm-based measure than the NH children. No significant differences were seen between the CI and HA groups in all of these measures except for the mean deviation of the pitch intervals. For both hearing-impaired groups, length of device use was significantly correlated with singing accuracy.
Conclusions: There is a marked deficit in vocal singing ability either in pitch or rhythm accuracy in a majority of prelingually-deafened children who have received CIs or fitted with HAs. Although an increased length of device use might facilitate singing performance to some extent, the chance for the hearing-impaired children fitted with either HAs or CIs to reach high proficiency in singing is quite slim.

1. Introduction

Singing can be characterized as a combination of music and language. People love to sing and yet, for the hearing impaired, the accuracy of singing is questionable. The main cause underlying the problem is likely due to the deficits in pitch perception that the hearing devices fail to support. Since a delicate closed-loop feedback mechanism between hearing and vocalization is of particular importance for humans to learn to control their vocal organs to produce appropriate and clear sounds [1], auditory deprivation at a very young age will result in poor self-monitoring and self-correction during articulation. For postlingually-deafened adults, hearing loss also influences vocalization due to a lack of instantaneous auditory feedback mechanism even though their pitch contour production is in general accurate [2,3].

Contemporary multichannel cochlear implants (CIs) are good at delivering phonetic information in quiet as well as proper timing and rhythmic information, but are subpar at delivering adequate pitch information [4–10]. This deficit is probably due to a small number of functional channels in CIs that limited the spectral resolution [10]. Yet, many factors other than the devices (such as poor neural survival and poor cognitive function) may potentially influence pitch perception ability of the hearing-impaired listeners with CIs [11,12]. Research in digital hearing-aids (HAs) has been focused on speech perception abilities of the users. With the improvement of HA technology, interest has grown into music perception as an indicator of quality of life. Many hearing-impaired people complain of reduced sound quality while listening to music through HAs [13]. A number of studies have reported reduced frequency selectivity arising from increased auditory filter bandwidths in listeners with cochlear hearing losses [14–18]. Poor frequency resolution due to damaged hair cells can lead to difficulty in perceiving discrete pitch patterns that cannot be overcome or compensated for with HAs. The reduced frequency selectivity due to the wider filter bandwidths may have a deleterious effect on pitch-based perception as the listener would

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be less capable of resolving the lower-order harmonics in the acoustic signals. In a study with both CI and HA users, Looi and colleagues [19] used a music test battery to evaluate several aspects of music perception. Their results showed that the two groups were almost identical for the rhythm test, with the HA group performing significantly better than the CI group on the pitch- and melody-related tests, suggesting that HAs may provide more reliable *F*0 information than CIs.

It appears that CI users can benefit from the use of the residual hearing in low frequencies whenever possible. In particular, two studies examined melody recognition in such CI users. Dorman and colleagues [20] studied a group of 15 conventional implant users who wore HAs on the contralateral ear and tested melody recognition with CIs alone or with CIs and HAs together. They found that the performance on melody recognition was better for these subjects under combined electrical-acoustical stimulation condition than that under electrical stimulation condition. Gfeller et al. [21] tested a group of 8 subjects with combined electrical and acoustical stimulation. These subjects were implanted with a short electrode that has only six electrodes on the electrode array that were placed in the basal end of the cochlea while their low-frequency region were kept undisturbed to make their relatively preserved low-frequency residual hearing usable. The study found that the subjects using such bimodal hearing performed significantly better than the CI users with the fully-inserted, long electrodes in the melody recognition test. Note that in both studies mentioned above, the ears with usable hearing presented with mild to moderate hearing loss only. In any case, the CI users with combined acoustical and electrical stimulations failed to achieve accurate or effective music perception as normal-hearing (NH) listeners did.

For tone-language-speaking CI users, the pitch-related tone variations in speech add to the challenges that are faced by these listeners. Previous studies have documented deficits in lexical tone production as well as in tone perception in tone-language-speaking children with CIs [22–30]. Few studies reported the effectiveness of HA on tone perceptions. Lee et al. showed that profoundly-deaf HA users performed similarly on tone perception to CI users [31], suggesting that HA users have difficulties in certain pitch-related tasks. However, Looi et al. indicated that HA users' pitch perception ability was significantly better than that of CI users and was comparable to listeners with NH [19,32]. Our recent study [33] showed that musical pitch and lexical tone performance with CIs are correlated, suggesting that they might share a common mechanism in electric hearing. Since tone production of children with CIs has been shown significantly worse than that of their NH counterparts [22–26], vocal singing could also be a problem with these children [5,9].

It is still uncertain whether HA users' pitch perception is superior to CI users although some evidence so far tends to indicate that usable acoustic hearing is helpful to perceive pitch [20,21]. If listeners who wear HAs and those with CIs do perform differently on the pitch perception, one can assume that their singing accuracy will be different. In a preliminary study on singing of prelingually-deafened children with CIs, we found that their pitch production rather than rhythm production was significantly poorer than the NH children [9]. In the present study, we increased the subject sample size and included an additional hearing-impaired group (i.e., HA group). We sought to examine the acoustic properties of vocal singing in two groups of Mandarin-speaking children (one with CIs and the other with HAs) and to compare the singing performance with that of the age-matched NH peers. Based on previous work, we hypothesize that both CI and HA children will show significant deficits in vocal singing performance as compared to the NH, age-matched children. The deficits will be especially prominent in pitch-based acoustic measures as opposed to rhythm-based measure. We also evaluate the correlation between various demographic factors and vocal singing accuracy as measured by the acoustic analysis.

2. Materials and methods

2.1. Subjects

Sixty-eight prelingually-deafened children, 42 boys and 26 girls, between the ages of 2.13–7.15 (Mean ± SD, 4.61 ± 1.28) years participated in the present study. Subjects were recruited from East China Normal University. All of the prelingually-deafened children had bilateral, severe-to-profound hearing impairments. The inclusion criterion was based on the child or the parents' claim of sing ability. Thirty-one subjects used bilateral digital HAs and 37 used unilateral CIs. Age at first HA fitting, for the HA group, ranged from 0.50 to 4.83 years, and duration of HA use ranged from 0.35 years to 5.58 years. Age at implantation, for the CI group, ranged from 0.58 to 6.63 years, and duration of CI use ranged from 0.52 to 5.50 years. In this group, 16 used the CI devices from Med-El, 11 from Cochlear, and 10 from Advanced Bionics. Demographic information of the two hearing-impaired groups is summarized in Table 1. As controls, 37 NH, typically-developing children (15 boys and 22 girls) between the ages of 3.08 and 6.33 years (Mean ± SD, 4.95 ± 0.92) were also recruited to participate in the present study. The NH status was based on parents' report. The use of human subjects was reviewed and approved by the Institutional Review Boards of Ohio University and East China Normal University.

2.2. Procedures

Vocal singing samples from both NH children and hearing-impaired children with CIs or HAs were recorded in a quiet room. Each child was asked to sing a song that he or she could sing the best. No imitation or instrument accompany was provided. Recording was accomplished using an Electro Voice omnidirectional microphone (Model RE50B) connected to an external sound card. The distance between the lips and the microphone was kept at approximately 10 cm. The output of the microphone was sent to a laptop computer with a sampling rate of 44.1 kHz and a resolution of 16 bits. The children participants produced a variety of songs that ranged in length from 12 to 44 notes. Although the assortment of songs chosen by individual child might affect the comparison of signing accuracy, allowing them to make their own choice helped to induce the best performance level. All songs selected by the subjects were Chinese children's songs that are simple and short with moderate pitch range. We were contented that the influence of song inconsistency is minimal.

Table 1
Demographic information of the cochlear implant (CI) and hearing aid (HA) groups (Mean ± SD).

	N	Chronological age (years)	Device fitting age (years)	Duration of device use (years)	Unaided PTA[a] (dB HL)	Aided PTA[b] (dB HL)
CI	37	4.64 ± 1.37	2.38 ± 1.41	2.26 ± 1.28	109.6 ± 13.7	36.1 ± 9.1
HA	31	4.57 ± 1.19	2.10 ± 1.28	2.47 ± 1.36	86.3 ± 15.0	47.5 ± 12.2

[a] Unaided PTA is the average threshold of 500, 1000, 2000, and 4000 Hz tested with pure tones presented through earphones.
[b] Aided PTA is the average threshold of 500, 1000, 2000, and 4000 Hz tested with warble tones presented in a sound field.

2.3. Acoustic analyses

The sung notes were isolated first using a sound processing program [CoolEdit 2000 (Syntrillium Software, Scottsdale, AZ)]. The fundamental frequencies (*F*0) of each note were computed from the steady-state portions of the sung note using an autocorrelation method realized in MATLAB (MathWorks, Natick, MA) environment. The steady-state portion was defined as the individual vowels portion with relatively stable amplitudes. The accuracy of *F*0 extraction was then manually checked to correct the errors caused by the autocorrelation algorithm [24,26,27]. The median value of the *F*0s in each note was taken as the *F*0 for that note. *F*0s were converted to semitones relative to C4 using the formula: semitone = $12 \times \log_2(F0/262)$. We then normalized the semitones of the sung song and the target song to their respective means of the entire song. The purpose of this normalization was to align the pitch contour of the sung song with the pitch contour of the target song to minimize any differences between the key in which the child sang the song versus the key in which the score was written. The duration of each note was also measured for the rhythm evaluation. Based on our previous work [9], the following five metrics were used to quantify the singing proficiency in the three groups of children: (1) percent correct of *F*0 contour direction of the adjacent notes, (2) *F*0 compression ratio of the entire song, (3) mean deviation of the normalized *F*0 across the notes, (4) mean deviation of the pitch intervals. These measurements represented the pitch-related accuracy of singing from four different aspects. For the fifth measurement, we used mean deviation of duration ratio between notes. We use this measurement instead of standard deviation of the note duration difference that we used in our previous preliminary study [9] because the current measure effectively eliminated the influence of absolute singing speed and therefore represented the rhythmic relationship among notes within the song more faithfully.

For each of the five metrics, a one-way ANOVA was used to compare the means of all three groups. When any of the one-way ANOVAs revealed a significant difference among group means, the Tukey–Kramer post hoc multiple comparison was used for pairwise comparisons. In addition, correlational analyses were performed to examine the relationship between various demographic factors and measures of singing performance.

3. Results

Fig. 1 shows the normalized *F*0s of the songs from three representative subjects of each of the three groups. In this figure, all subjects sang the same target song, the Chinese version of Frère Jacques, which happened to be the most frequently chosen song. The target notes are represented by gray lines with open symbols, and the sung notes from each child are represented by black lines with filled symbols. The pitch contours of the sung notes and the music scores were aligned with each other by subtracting the mean in semitones from the respective contours. Note that all of the pitch-related measures (see below) can be derived from this type of pitch contour graphs but the duration of the notes is not represented in the graphs. The NH children showed good alignment between the singing pitch contour and the target contour (Fig. 1, top panels) whereas the HA children (Fig. 1, middle

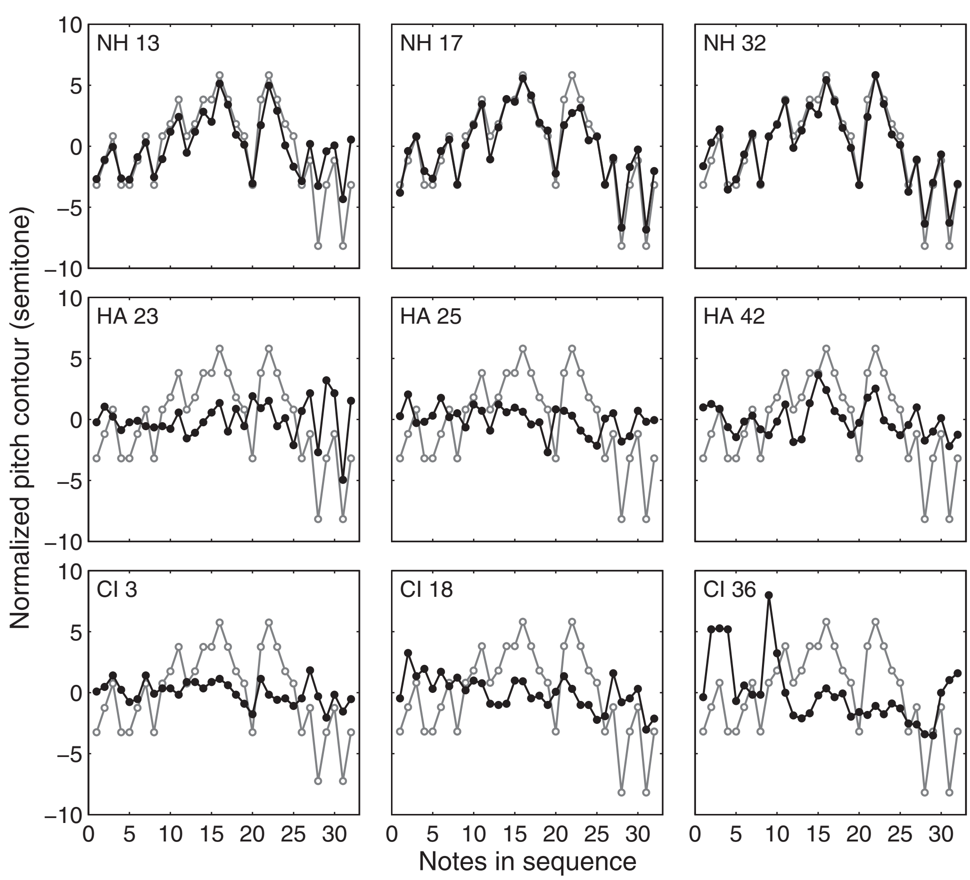

Fig. 1. Pitch contours for three NH children (top panels), three HA children (middle panels) and three CI children (bottom panels). All these subjects sang the same song, the Chinese version of Frère Jacques. For each subject (each panel), the gray lines and open symbols represent the target song, whereas the black lines and filled symbols represent the pitch contour of the song produced by the subject. Both the target song and the recorded song were normalized to their respective semitone means. The rhythm information was removed.

panels) and the CI children (Fig. 1, bottom panels) showed very poor alignment of the two contours. The sung contour from the hearing-impaired children tended to have a narrower variation range of pitch than did the NH children and varied greatly across individuals.

Five metrics were developed in our laboratory to quantify singing accuracy. The first metric was percent correct of *F*0 contour direction. In this metric, if any two adjacent notes of the sung song went in the same direction as the target scores, they were counted as correct irrespective of the produced interval size. Any adjacent notes that didn't vary in pitch in the target were not counted. The percent correct of contour direction was calculated by dividing the number of correct pitch changes, sung by the individual child, by the total number of pitch changes in the target song. The mean scores (% correct) for the NH, HA, and CI groups were 93.0 ± 8.2, 66.3 ± 17.4, and 58.0 ± 16.2 (mean ± SD), respectively (Fig. 2A). Note that the chance performance is 50% correct in this metric. A one-way ANOVA showed a significant difference among the three groups ($F(2,35) = 59.78$, $P < 0.001$). The Tukey–Kramer post hoc multiple comparison showed that the contour direction scores of the CI and HA groups were not significantly different from each other ($P > 0.05$), and the NH group performed significantly better than both the CI and HA groups (both $P < 0.01$).

Compression ratio of songs was calculated by dividing the sung pitch range by the expected pitch range in semitones of the entire song. For example, if a child sang a song with a pitch range of 6 semitones and the pitch range of the target score was12 semitones, then the compression ratio would be 0.5 (i.e., 6/12). Ideal singing has a compression ratio of 1. Any compression ratio <1or >1 indicates compression or expansion of the pitch range. The mean score (mean ± SD) for the NH, HA, and CI group was 0.89 ± 0.23, 0.63 ± 0.23, and 0.73 ± 0.37, respectively (Fig. 2B). A one-way ANOVA showed that there was a significant difference among the three groups ($F(2,35) = 7.31$, $P = 0.001$). The Tukey–Kramer post hoc multiple comparison showed that the pitch compression ratio of the NH group was significantly larger than that of both the HA and CI groups (both $P < 0.05$), indicating less compression in the NH children. The amount of pitch compression between the HA and CI groups was not statistically significantly different ($P > 0.05$).

Mean deviation of the normalized *F*0 across notes was obtained by calculating the absolute semitone differences, note by note, between the two normalized pitch contours (i.e., the pitch contour that subjects sang and the contour of the target song) and then averaging across all notes for each subject. The mean scores (mean ± SD) for the NH, HA, and CI group was 1.19 ± 0.53, 2.54 ± 0.67, and 2.72 ± 0.69 semitones, respectively (Fig. 2C). A one-way ANOVA showed significant differences among the three groups ($F(2,35) = 62.83$, $P < 0.001$), and the Tukey–Kramer post hoc multiple comparison showed that children in both the CI and HA groups had significantly larger mean deviations of the normalized *F*0s than did the children in the NH group (both $P < 0.01$). The mean deviation between the CI and HA groups is not statistically significantly different ($P > 0.05$).

While the mean deviation of the normalized *F*0 described above reflects the degree of consistency between singing pitch contour and target pitch contour, it can be affected by how the pitch contours are normalized. To overcome such a potential effect, we further developed a mean deviation of the pitch intervals to capture the relative pitch relationship across notes within a song. In this metric, pitch intervals in semitones were measured for all adjacent notes of the song and the target scores. Then, the mean of the absolute differences in the pitch interval sizes between the sung song and the target scores was calculated. The mean score (mean ± SD) of the mean deviation of pitch intervals for the NH, HA, and CI groups was 1.11 ± 0.65, 2.44 ± 0.76, and 2.89 ± 0.82 semitones, respectively (Fig. 2D). A one-way ANOVA showed that there were significant differences among the three groups ($F(2,35) = 56.50$, $P < 0.001$). The Tukey–Kramer post hoc multiple comparison showed that the children who used CIs and HAs had significantly larger values of interval deviation than did the NH children (both $P < 0.01$). For the two hearing-impaired groups, the CI group had a significantly larger interval deviation than the HA group ($P < 0.05$).

All of the above-described four metrics were based on the pitch or pitch contour of the singing. Our final metric, mean deviation of duration ratio between notes, was derived to capture the singing accuracy in the rhythm aspect. In this rhythm-based metric, the ratio of duration between each pair of two adjacent notes was

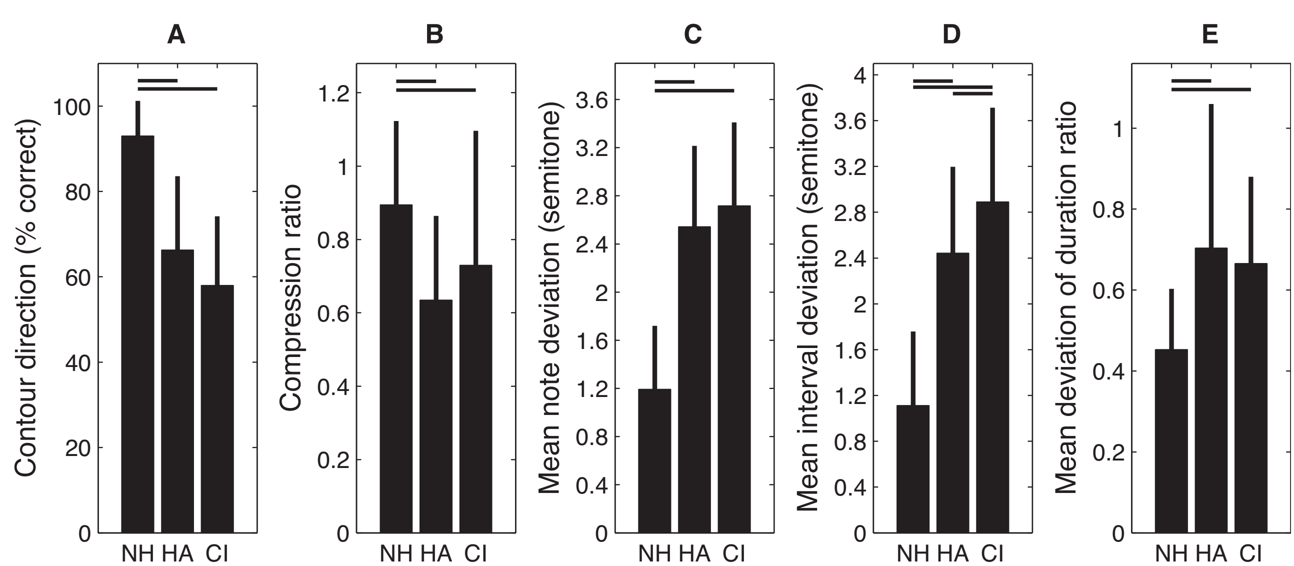

Fig. 2. Five metrics used for evaluating singing accuracy in the three subject groups. The five metrics include: (A) contour direction, (B) compression ratio, (C) mean note deviation, (D) mean interval deviation, and (E) Mean deviation of duration ratio between notes. In each panel, the bars from left to right, represents performance of the NH, HA, and CI groups, respectively. The error bars represent the SDs. The horizontal bars on the top of each panel indicate statistically significant differences between the groups that the horizontal lines span.

calculated for both the sung song and the target song. Then, the mean of the absolute differences between these two series of ratio values was calculated. The advantage of using this metric is that it is independent of the absolute speed of singing. As long as the singer keeps a consistent rhythmic relationship among notes as the target rhythm, the mean deviation of duration ratio would be small. The mean score (mean ± SD) for the NH, HA, and CI groups was 0.45 ± 0.15, 0.70 ± 0.36, and 0.67 ± 0.21, respectively (Fig. 2E). A one-way ANOVA showed differences among the three groups ($F(2,35) = 10.53$, $P < 0.001$). The Tukey–Kramer post hoc multiple comparison showed that the CI and HA groups had significantly larger mean deviations of duration ratio than did the NH group (both $P < 0.01$), but the CI and HA children did not differ significantly ($P > 0.05$).

Finally, correlational analyses, using data from both the CI and HA groups, were performed to examine whether singing performance was correlated with demographic factors including chronologic age, duration of CI or HA use, and age of CI implantation or initial HA fitting. Only statistically significant results from these numerous analyses are shown in Fig. 3 for the HA group and Fig. 4 for the CI group. For the HA group (Fig. 3), $F0$ contour direction of the adjacent notes, mean deviation of the pitch intervals, and mean deviation of duration ratio were correlated with duration of hearing aids use, and mean deviation of the pitch intervals was also correlated with chronologic age in this group. ($0.36 < |r| < 0.53$, all $P < 0.05$). For the CI children (Fig. 4), percent correct of $F0$ contour direction, mean deviation of the pitch intervals and mean deviation of duration ratio were correlated with length of CI use ($0.35 < |r| < 0.46$, all $P < 0.05$). It is worth noting that the type of CI devices did not show any effects on the singing performance.

4. Discussion

The present study extended our previous research on vocal singing of pediatric CI users and evaluated for the first time the singing ability of pediatric hearing-impaired HA users. In all of the pitch-based measures used to assess singing production, children with CIs or HAs performed significantly poorer than the NH children. Their pitch contour did not follow that of the scores and their pitch range was dramatically compressed. Individual sung notes were greatly deviated from the target notes and the sung interval sizes were not complied with the target interval sizes. Previous studies on singing accuracy of pediatric CI users showed that children with CIs generally produced inaccurate pitch in singing [5,9]. Results of the present study confirmed such findings with a larger sample size ($N = 37$). Moreover, given the negative appraisal of the HA users on music appreciation [13], the finding

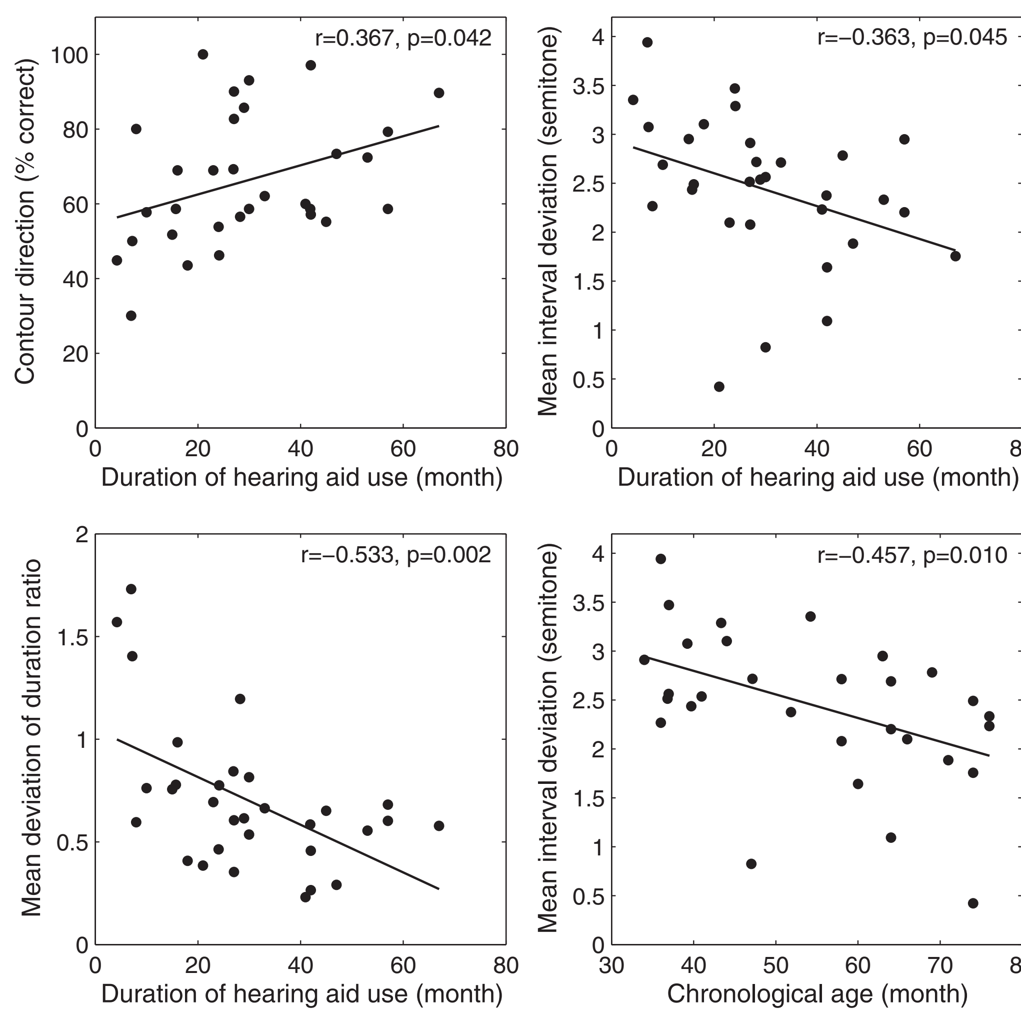

Fig. 3. Correlational analyses for the HA group. The upper-left, upper-right, and lower-left panels represent the correlation between duration of HA use and contour direction, mean interval deviation, and mean deviation of duration ratio between notes, respectively. The lower-right panel represents the correlation between chronological age and mean interval deviation. The correlation coefficient r and P values are shown in the upper-right corner.

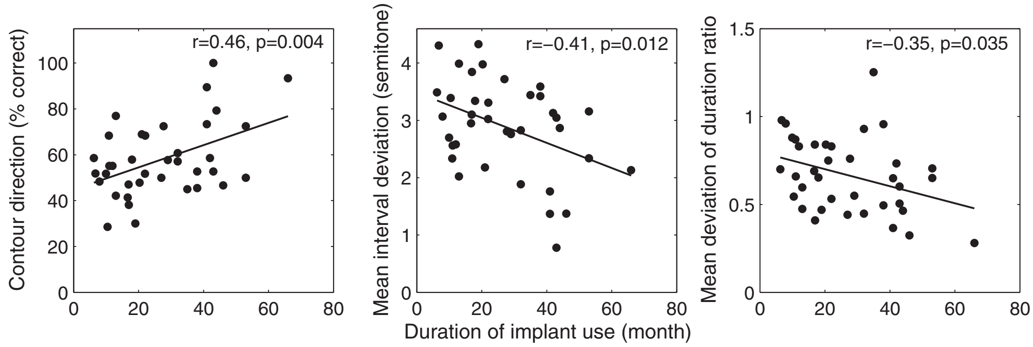

Fig. 4. Correlational analyses for the CI group. The panels from left to right represent the correlation between duration of CI use and contour direction, mean interval deviation, and mean deviation of duration ratio between notes, respectively. The correlation coefficient *r* and *P* values are shown in the upper-right corner.

that the singing accuracy of pediatric HA users was significantly worse than that of the NH subjects was consistent with our hypothesis.

The spoken language development of the hearing-impaired children lags significantly when compared to their age-matched, typically-developed children and is attributed, at least in part, to their degraded ability to perceive [34]. Acoustic properties of music are more complicated than speech in terms of spectral, temporal, and timbral complexity with a greater dynamic range [11]. Amplitude compression is an inevitable consequence of all hearing devices. More importantly, the speech processing strategies used in the contemporary CIs do not provide users the amount of pitch information necessary for perceiving the wide range of pitch variation in music. In studies of lexical tone perception and production on pediatric CI users, whereas the tone perception performance is usually poor, large individual variations in tone production performance do exist [22–27]. For users with HAs, the amplification and signal processing do not compensate for the degradation of frequency sensitivity accompanying with the cochlear damage [14–18]. Therefore, poor singing accuracy as observed in the present study is likely stemmed from poor pitch perception ability in the hearing-impaired children fitted with either CIs or HAs.

The exact amount of frequency resolution in the CI and HA users are likely to be different from each other. Looi et al. found that the HA users performed significantly better than the CI users on the pitch and melody tests [19]. In the present study, we found that the singing accuracy of the HA group was not significantly different from that of the CI group except in one of the pitch-based measures (i.e., pitch interval deviation). The CI group sang with a less accurate pitch interval size than the HA group did (see Fig. 2D). The unaided pure tone average threshold (PTA) was evidently higher in the CI group than the HA group (Table 1). However, the aided PTA was actually lower in the CI group than the HA group. Therefore, the differences in singing proficiency of the two hearing-impaired groups could not be simply explained by the hearing thresholds. Either spectral or temporal cues can be used to perceive pitch. For the CI users, spectral cue is smeared by the limited number of channels, the diffused electric current as well as the possible frequency mismatch in cochlea, and might be further aggravated by the sparse neural survival of the spiral ganglion cells. The greatest limitation with the temporal pitch cue is the apparent 300-Hz upper limit in most CI users [35,36] although some CI users can discriminate higher rate pitch [37]. For prelingually-deafened children with CIs, their temporal sensitive was found significantly poorer than postlingually-deafened adult CI users [38]. It is likely that using acoustic hearing, the HA users might have somewhat better pitch perception ability than the CI users despite the HA users' widened cochlear filters. However, a direct psychophysical comparison of such ability has not been performed.

The mean note deviation and mean interval deviation of the CI groups were 2.72 and 2.89 semitones, respectively (see Fig. 2C and D). It is interesting that these values were surprisingly close to the perceptual results reported recently by Jung et al. [38] who found that the average complex pitch direction discrimination by their pediatric implant users was 2.98 semitones. In a recent study on lexical tone perception and production, we demonstrated a moderate correlation ($r = 0.56$) between tone perception and production in a large group ($N = 73$) of prelingually-deafened children with CIs [23]. Although good pitch perception is the prerequisite of satisfactory pitch production [22,39], perception and production may involve different, complicated processes of the central nervous system and complex executive functions [40]. Music perception requires high-level integrative functions which depend on the degree of maturation and integrity of central nervous system. For the prelingually-deafened children, hearing deprivation followed by a series of morphological and physiological changes throughout the auditory system [41–43] will ultimately influence the perception of music. Hearing deprivation may have also caused delays in development of the central nervous system and degradation of the central auditory functions and other higher functions that control the vocal singing. Even in the NH children, their singing showed a deviation of pitch intervals of approximately 1.1 semitones (see Fig. 2D) on average, which is larger than the pitch perception results of 0.3 semitones reported by Stalinski et al. [44]. Therefore, we would caution direct prediction from pitch perception to pitch production because perception is probably not the only determinant to production.

The HA and CI groups performed similarly in the rhythm-based measure but both performed significantly worse than the NH group (see Fig. 2E). This latter result is inconsistent with previous studies [5,9], in which the CI children's rhythm accuracy in singing was comparable to the NH controls. However, it is worth noting that the average chronological age of CI participants in the present study was younger than the previous studies, 4.64 years versus 7.61 years in the Nakata et al. study [5] and 7.70 years in the Xu et al. study [9]. Even for NH children, the duration sensitivity as measured by duration discrimination is not adult-like until the age of 8–10 years [45]. The detailed developmental pattern of duration sensitivity in hearing-impaired children is yet to be determined. It appears that the young hearing-impaired children have not fully developed the ability to produce accurate rhythm. Although the current CI systems can faithfully deliver rhythmic information and users with CIs or HAs have been reported to perform well in rhythm perception tasks [4,19,46–48], our data from 68 prelingually-deafened children indicate that they can not produce accurate rhythm patterns of the song, at least in those young ages.

Large variations in singing performance were observed in all children, NH and hearing impaired alike (see Fig. 2). For the NH children, we found no correlation between the singing performance and their chronologic age. It is possible that our age range of the sample was fairly small, from 3.08 to 6.33 years old. In the hearing-impaired groups, we found that three out of five measures, i.e., $F0$ contour direction of the adjacent notes, mean deviation of the pitch intervals, and mean deviation of duration ratio were weakly correlated with the duration of device use (Figs. 3 and 4). For the HA group, mean deviation of the pitch intervals was also weakly correlated with chronologic age (Fig. 3). These correlations could be the consequence of experience, training, or maturation of their auditory processing ability, which we are unable to separate out from the present study. Nonetheless, the fact that singing proficiency improves with duration of device use is encouraging. Previous studies have indicated that music training helps to improve pitch perception in prelingually-deafened children with CIs [49,50]. Taken together, data from previous reports and the present study would imply that hearing-impaired children might improve their proficiency of singing through habilitation although we should also keep our expectations realistic.

5. Conclusions

In the present study, we found that some prelingually-deafened children, with severe-to-profound hearing loss, developed some form of vocal singing through the use of CIs or HAs. Their singing performance was apparently not as good as that of their age-matched NH children in terms of either pitch-related or rhythm-based measures. The performance between prelingually-deafened children with CIs and HAs on these measures was not significantly different except for the pitch interval deviation, in which the HA users performed slightly more accurately. There is a tremendous individual difference in singing performance in the hearing-impaired children. Length of device use shows weak/moderate but significant correlation with pitch and rhythm accuracy in singing suggesting that appropriate music training could be promising in improving singing proficiency of hearing-impaired children with hearing devices.

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