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The production of Mandarin tones by early-implanted children with cochlear implants: effects from the length of implantation

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Abstract

Children with cochlear implants (CIs) learning tonal languages such as Mandarin Chinese face challenges in acquiring tones due to the limitation of devices in coding pitch information. Mandarin has four lexical tones and a neutral tone. A recent study [7] showed that Mandarin-learning preschoolers who were early-implanted (implanted between 1-2 years) were able to produce acoustically target-like tones but with a large amount of variability. This variability might be driven by the small sample size (only seven children were tested in that study) and the differences in length of CI experience. Therefore, the current study tested more early-implanted children and explored the effect of CI experience on their tonal acquisition. Forty-four 3-year-old normal-hearing (NH) controls and 28 early-implanted children (implanted between 1-2 years) with 1-6 years of CI experience were tested. Lexical tone and neutral tone productions were elicited and acoustically compared across groups. The results showed that children with more than 3 years of CI experience had typical tonal productions, acoustically similar to those of NH children, while those with less experience produced less distinguishable tones. These results provide acoustic evidence showing that the combination of both early implantation and longer CI experience facilitates children's acquisition of target-like tones.

Index Terms: language acquisition, Mandarin Chinese, lexical tone, neutral tone, cochlear implants

1. Introduction

The development and availability of cochlear implants (CIs) has made oral speech communication possible for many children with profound hearing loss. However, for children with CIs learning tonal languages such as Mandarin Chinese, acquiring typical tonal productions can be challenging. This is because pitch information, which is critical in differentiating tones, is not transmitted effectively via CIs as a result of the limited number of channels used in these devices to deliver a wide range of speech frequencies [1].

Mandarin has four lexical tones and a neutral tone category [2] (Figure 1). The four lexical tones are critical in differentiating word meanings, primarily contrasting in pitch contours: Tone 1 (T1; level), Tone 2 (T2; rising), Tone 3 (T3; dipping) and Tone 4 (T4; falling) [3]. In addition, neutral tone is a short toneless category, also referred to as Tone 0 (T0), exhibiting contextually conditioned pitch realizations. For instance, its pitch pattern is **falling** after T1/2/4 and **level/rising** after T3 [4].

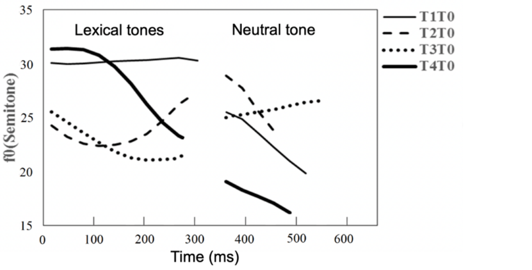

Figure 1. *Pitch contours of lexical tones and neutral tone in disyllabic words.*

Neutral tone is only carried by weak syllables, such as the second syllable of reduplicatives, e.g., the kinship-term "ma1 **ma0**" *mother*, and some function words, e.g., the possessive particle "de0" in the word "niu2 **de0**" *cow's*. Some neutral tone words are lexicalized and familiar to children, such as kinship reduplicatives which are used frequently in daily speech communication. Others are productive, such as possessives, in which the possessive particle "de0" can be combined with any noun to form a novel item. It has been demonstrated that normal hearing (NH) 3-year-olds are already able to produce distinct lexical tone pitch contours and target-like neutral tones for both reduplicatives and possessives [4-5].

For children with CIs, however, it has been shown that acquiring typical lexical tone productions is challenging, while early implantation and longer CI experience have been thought to lead to better tonal productions. For instance, based on perceptual coding, Han et al. [6] found strong correlations between implantation age and children's lexical tone production accuracy (r = -0.57, $p < 0.05$) as well as between length of CI experience and tonal production accuracy ($r = 0.56$, $p < 0.05$). However, since few studies have used acoustical analysis to compare the tonal productions of NH children with those of children with CIs, it was still unclear whether children with early implantation and/or longer CI experience can produce lexical tones that are acoustically comparable to those of NH children, and whether they are able to produce target-like pitch variation for neutral tones across tonal contexts.

These issues were partly addressed by a recent study from Tang et al. [7]. In that study, the authors compared lexical tone and neutral tone productions from NH 3-year-olds and CI groups (3-7-year-olds) with different ages at implantation (1-2 years, 2-3 years, 3-4 years and 4-5 years) and different lengths of CI experience (3-4 years, 2-3 years, 1-2 years and less than 1 year). The results showed that only the early-implanted children, i.e., implanted between 1 to 2 years, produced lexical tone and neutral tones that were generally comparable to those

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of NH children. However, those who were implanted after the age of 2 produced lexical tones and neutral tone syllables with flatter and less distinguishable pitch contours across tonal contexts, even for those with longer CI experience, i.e., 3-4 years. These results therefore highlight the importance of early implantation for children with CIs to acquire typical Mandarin tonal productions, including both lexical tones and neutral tone.

However, in the study by Tang et al., there were only seven children with early implantation (before age 2); this calls for a larger study with more early-implanted children to assess the reliability and generalizability of those results. Furthermore, even for those early-implanted children, the lexical tones produced still showed a large amount of individual variability, and the neutral tone productions only exhibited the expected pitch variation in (familiar) reduplicatives but not in the novel word (productive) possessive context. This hints at the possibility that there might be other factors, probably the length of CI experience, that contribute to the variability in these early-implanted children's tonal productions. There is evidence suggesting that it is the combined effect of both early implantation and longer CI experience that accounts for better language outcomes [8]. If this is also the case for tonal development, we would expect that, within a larger early-implanted group, those who have had longer CI experience might produce tonal productions that are closer to those of their NH peers than those who have shorter CI experience.

Based on the study of Tang et al., the current study focused on a new/larger group of early-implanted children (implanted between 1-2 years), exploring the effect of CI experience on their tonal productions, including both lexical tones and neutral tone. We asked whether the combined effect of early implantation and longer CI experience facilitates these children's ability to produce Mandarin tones that are acoustically comparable to those of their NH peers.

2. Method

2.1. Participants

The participants included forty-four NH 3-year-old controls who had already acquired adult-like acoustic values for both lexical tones and neutral tone [4, 5], and 28 3-7-year-olds who were implanted with CIs early (between 1 to 2 years). All were recruited from preschoolers and rehabilitation centers in Beijing. The children with CIs were divided into three groups according to length of CI experience: 3-6 years (CI Exp 3-6 yrs., 10 children), 2-3 years (CI Exp 2-3 yrs., 11 children) and 1-2 years (CI Exp 1-2 yrs., 7 children).

2.2. Stimuli

Four picturable monosyllabic words and eight disyllabic neutral tone words were used as stimuli. The four monosyllabic words carried different lexical tones (T1-4), i.e., "shu1" *book*, "qiu2" *ball*, "gu3" *drum* and "hua4" *painting*. The eight neutral tone words consisted of four (familiar) kinship reduplicatives and four (productive) possessives. Within each type, syllable 1 carried different lexical tones (T1-4) and syllable 2 always carried T0. We predicted that children with CIs might perform better in producing the familiar reduplicatives than the productive possessives based on the results of Tang et al. [7].

2.3. Procedure

All participants were tested in a quiet room. A picture-naming task was adopted to elicit their tonal productions. To elicit lexical tones, in each trial, a picture corresponding to the target word was presented on the screen, such as a horse for the word "ma3" *horse*, and the participant was asked to produce the name of the picture. To elicit the (kinship) reduplicative neutral tone words, pictures illustrating family members were presented on the screen and the participant was asked to produce names of these familiar members. To elicit the possessive neutral tone words, e.g., "niu2 **de0**" *cow's*, a cow was presented on the screen with an animation on its tail, and the participant was asked "whose tail is this?". Participants' productions were recorded via a head-mounted microphone.

2.4. Coding and measurement

Participants' lexical tone and neutral tone productions were acoustically coded in Praat [9]. For the pitch analysis, ten equidistant pitch points were extracted from 5%-95% of the vowel portion of each syllable. The extracted pitch values (in Hz) were then transformed into semitones to better match the human perception [10-11], using the following formula: semitone = 12 * $\log_2$ (Hz value/50Hz). To minimize possible interspeaker variation in pitch, the semitone values were then *z*-score normalized against the mean pitch value and the standard deviation (SD) of pitch values across all tokens produced by each speaker, using the following formula:

$$\text{Normalized pitch} = (\text{Pitch} - \text{Pitch}_{mean}) / \text{Pitch}_{SD}.$$

2.5. Statistical analysis

Growth curve analysis (GCA) was adopted to compare the group difference in pitch contours for lexical tone and neutral tones, using two pitch parameters: pitch slope (the linear trend) and curvature (the quadratic trend) [12]. This analysis was implemented using the linear mixed regression model based on the R package "lme4" [13]. The statistical significance was obtained based on *F*-tests using the "lmerTest" package [14]. When significant main effects or interactions were observed, Tukey-HSD pairwise comparisons were adopted using the "lsmeans" package [15].

3. Results

3.1. Lexical tones

Figure 2 illustrates the pitch contours of the lexical tone productions from the NH children and the children with CIs, grouped according to length of CI experience. It has been suggested that NH 3-year-olds were already able to produce distinct lexical tone pitch contours, i.e., level T1, rising T2, dipping T3 and falling T4 [4-5]. This is also consistent with our NH children results here.

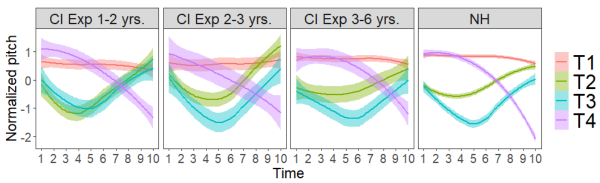

Figure 2: *Lexical tone pitch contours across groups.*

To compare the group difference in lexical tone productions, a linear mixed regression model was conducted on the pitch **slope** and **curvature** across tones and groups. The model included two fixed factors "Tone" (T1, T2, T3 and T4) and "Group" (NH, CI Exp 3-6 yrs., CI Exp 2-3 yrs. and CI Exp 1-2 yrs.), and a random factor "Participant" (72 children). The results showed that the interaction between "Tone" and "Group" was significant on pitch slope (F (9, 2530) = 2.298, $p < 0.05$) and curvature (F (9, 2530) = 2.777, $p < 0.01$), indicating that there were group difference in pitch contours across tones.

Two Tukey-HSD pairwise comparisons were then performed to examine (1) whether tones were distinguishable for each group, and (2) whether the CI groups differed from NH controls in their acoustic realization for each tone. The results of the first comparison showed that children with 3-6 and 2-3 yrs. of CI experience produced distinct pitch contours for all tones, just like the NH children. However, children with only 1-2 yrs. of CI experience did not differentiate T2 and T3 (Table 1). The results of the second comparison showed that children with CIs differed from NH children in their acoustic realization of T4, with less falling pitch contours. At the same time, children with 2-3 and 1-2 yrs. of CI experience also produced a non-NH like T2, with more curvature (Table 2).

Table 1: *Results of Tukey-HSD post-hoc comparison on tone difference for each group (S = Slope, C= Curvature; asterisks indicate significant findings: p < 0.05*, p < 0.01**, p < 0.001***).*

Tone	Para-meter	NH	CI 1-2 yrs.	CI 2-3 yrs.	CI 3-6 yrs.
T1 vs. T2	S	***	**	**	*
	C	***	*	***	
T1 vs. T3	S	***			
	C	***	*	***	***
T1 vs. T4	S	***	***	***	***
	C	***			*
T2 vs. T3	S			*	
	C	***			*
T2 vs. T4	S	***	***	***	***
	C	***	***	***	***
T3 vs. T4	S	***	***	***	***
	C	***	***	***	***

Table 2: *Results of Tukey-HSD post-hoc comparison on group difference of tones (S = Slope, C= Curvature; asterisks indicate significant findings: p < 0.05*, p < 0.01**, p < 0.001***; comparisons between CI groups are not presented due to the limited space).*

Group	T1		T2		T3		T4	
	S	C	S	C	S	C	S	C
CI 1-2 yrs. vs. NH				*			**	*
CI 2-3 yrs. vs. NH				*			*	
CI 3-6 yrs. vs. NH							*	

These results suggested that only children with 3-6 yrs. and 2-3 yrs. of CI experience were able to produce distinct lexical tone pitch contours, though their tonal productions were not fully NH-like, especially for T4. Children with 1-2 yrs. of CI experience, however, confused T2 productions with T3.

3.2. Neutral tone

Figure 3 shows pitch contours of reduplicative and possessive neutral tone syllables across tonal contexts from the NH children and the children with CIs. It has been suggested that NH 3-year-olds were already able to correctly produce the neutral tone pitch patterns across tonal contexts for both (familiar) reduplicatives and (productive) possessives, i.e., falling after T1/2/4 and rising/level after T3, which is also consistent with our NH results here.

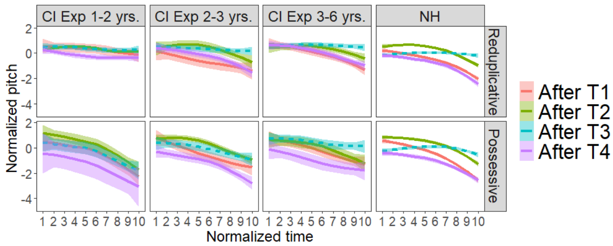

Figure 3. *Neutral tone pitch contours across groups.*

To compare the group differences in neutral tone productions, a linear mixed regression model was conducted on the pitch slope and curvature of neutral tone productions across tonal contexts and groups. Three fixed factors "Tonal context" (after T1/2/4 and after T3), "Type" (reduplicative and possessive) and "Group" (NH, CI Exp 3-6 yrs., CI Exp 2-3 yrs. and CI Exp 1-2 yrs.), and a random factor "Participant" were included in the model. The results showed that the two-way interaction of "Tonal context × Group" was significant on the pitch slope (F (3, 4650) = 14.589, $p < 0.001$), and there were no higher order interactions, suggesting that different groups showed different pitch variations of neutral tone across tonal contexts irrespective of the types of neutral tone words (reduplicatives or possessives).

Two Tukey-HSD post-hoc tests were then performed on this interaction to examine (1) whether tonal contexts affect the acoustic realization of the neutral tone (i.e. after T1/2/4 vs. T3) for each group, and (2) whether children with CIs differed from NH children in their acoustic realizations. The results of the first comparison showed that children with 3-6 and 2-3 yrs. of CI experience produced the expected patterns, just like the NH children: NH $\beta = -10.811$, t (4580) = -19.58, $p < 0.001$; CI Exp 3-6 yrs. $\beta = -5.49$, t (4587) = -4.08, $p < 0.001$; CI Exp 2-3 yrs. $\beta = -3.58$, t (4601) = -2.61, $p < 0.01$). However, children with only 1-2 yrs. of CI experience did not vary the acoustic realization of neutral tone syllables across the different tonal contexts ($\beta = -1.83$, t (4604) = -0.78, $p = 0.437$; Table 3).

The results of the second comparison showed that children with CIs did not differ from NH children in their acoustic realization of neutral tone when it followed T1/2/4. However, CI groups differed from NH children in how they acoustically realized neutral tone when it followed T3. While children with 3-6 yrs. of CI experience did not differ from NH children, the other two groups produced neutral tone with less rising pitch contours than the NH children (Table 4).

Table 3. *Results of the Tukey-HSD post-hoc comparison on the pitch slope between tonal contexts for each group (asterisks indicate significant findings: p < 0.05*, p < 0.01**, p < 0.001***).*

Context	NH	CI 1-2 yrs.	CI 2-3 yrs.	CI 3-6 yrs.
After T1/2/4 vs. After T3	***		**	***

Table 4. *Results of the Tukey-HSD post-hoc comparison on the pitch slope of neutral tone between groups for each context (asterisks indicate significant findings: p < 0.05*, p < 0.01**, p < 0.001***; comparisons between CI groups are not presented due to the limited space).*

Group	After T1/2/4	After T3
CI 1-2 yrs. vs. NH	*	
CI 2-3 yrs. vs. NH	**	
CI 3-6 yrs. vs. NH		

These results suggest that children with 3-6 yrs. and 2-3 yrs. of CI experience have produced the expected pitch variation of neutral tone syllables across tonal contexts, but only the children with 3-6 yrs. of CI experience were able to produce neutral tone pitch contours similar to those from NH children. Children with 1-2 yrs. of CI experience, however, did not vary the acoustic realization of neutral tone across different tonal contexts, suggesting that they need more time to acquire tones like those of their NH peers.

4. Discussion

The current study explored the effect of CI experience on the acquisition of Mandarin tones, including lexical tones and neutral tone, by children implanted early, i.e., between 1 and 2 years. Compared to children with less than 3 years of CI experience, those with more experience produced distinct lexical tones and neutral tones, which were acoustically similar to productions by the NH children. Children with 2-3 yrs. of CI experience were also able to produce distinct lexical tones and expected tonal patterns for neutral tone, but their tonal productions were less NH-like. However, children with only 1-2 years of experience produced less distinct lexical tones, with T2 being confused with T3, and they did not vary the acoustic realization of neutral tone in different tonal contexts.

The present study therefore extends the results of Tang et al. [7] in which only seven early-implanted children were tested. They found that early-implanted children were able to produce typical lexical tone and neutral tone productions. Extending their findings, our results suggest that CI experience is also important, even for early-implanted children.

Our results are consistent with other findings from English suggesting that the combined effect of early implantation and longer CI experience leads to better speech production ability (of vowels and consonants) [8]. The current results thus suggest that these two factors are critical for the acquisition of both segments and lexical tones.

There are two possible reasons for why both early implantation and longer CI experience are critical. First, the effect of early implantation has been suggested to relate to the developmental plasticity of the central auditory cortex, which maintains maximal plasticity in the early ages [16]. There is also evidence suggesting that infants show maximal sensitivity to tones in the first two years of life [17]. Therefore, it might be critical for children with hearing impairment to receive implantation within this time window so that they will have early access to tonal information. Second, similar to NH children, children with CIs also need to receive enough input to develop typical phonological representations and master tonal production skills. It has been suggested that NH children have acquired both lexical tones and neutral tone by the age 3 [4, 5]. This implies that children with CIs might also need 3 years of language input/CI experience to achieve this ability, in addition to early implantation.

One of the central questions in the language development of children with CIs is the contribution of age at implantation and CI experience. The two factors were typically examined separately [7, 18]. However, our results imply that, at least in the tonal development, the two factors interact with each other, where one factor might enhance the effect of the other factor. The current study therefore has implications for future studies to investigate the interaction between the two factors in other aspects of language development.

5. Conclusion

This study demonstrates the combined effect of early implantation and longer CI experience in facilitating children with CIs to acquire typical tonal productions. Early implantation (before age 2) is a necessary but not sufficient factor in tonal development for children with CIs, who also need to accumulate enough CI experience/language input to form robust tonal representations, i.e., at least 3 years. Our results therefore have both practical and clinical implications for identifying factors that could lead to better language outcomes for children with CIs learning a tone language.

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7. References

[1] A. E. Vandali, R. J. M. van Hoesel, "Enhancement of temporal cues to pitch in cochlear implants: Effects on pitch ranking," *The Journal of the Acoustical Society of America*, vol. 132, no. 1, pp. 392-402, 2012.

[2] M. Yip, *Tone*, Cambridge: Cambridge University Press, 2002.

[3] Y. Xu, "Contextual tonal variations in Mandarin," *Journal of Phonetics*, vol. 25, no. 1, pp. 61-83, 1997.

[4] P. Tang, I. Yuen, N. Xu Rattanasone, L. Gao and K. Demuth, "Acquisition of weak syllables in tonal languages: Acoustic

evidence from neutral tone in Mandarin Chinese," *Journal of Child Language*, vol. 46, no. 1, pp. 24-50, 2019.

[5] P. Tang, I. Yuen, N. Xu Rattanasone, L. Gao and K. Demuth, "The acquisition of phonological alternations: The case of the Mandarin tone sandhi process," *Applied Psycholinguistics*, vol. 40, no. 6, pp. 1495-1526, 2019.

[6] D. Han, N. Zhou, Y. Li, X. Chen, X. Zhao and L. Xu, "Tone production of Mandarin Chinese speaking children with cochlear implants," *International Journal of Pediatric Otorhinolaryngology*, vol. 71, no. 6, pp. 875-880, 2007.

[7] P. Tang, I. Yuen, N. Xu Rattanasone, L. Gao and K. Demuth, "The acquisition of Mandarin tonal processes by children with cochlear implants," *Journal of Speech, Language, and Hearing Research*, vol. 62, no. 5, pp. 1309-1325, 2019.

[8] C. M. Connor, H. K. Craig, S. W. Raudenbush, K. Heavner and T. A. Zwolan, "The age at which young deaf children receive cochlear implants and their vocabulary and speech-production growth: is there an added value for early implantation?" *Ear and Hearing*, vol. 27, no. 6, pp. 628-644, 2006.

[9] P. Boersma and D. Weenink, Praat: doing phonetics by computer [Computer program]. Version 6.0.52, retrieved 2 May 2019 from http:// www.praat.org/, 2019.

[10] P. Tang, I. Yuen, N. Xu Rattanasone and K. Demuth, "Phonetic enhancement of Mandarin vowels and tones: Infant-directed speech and Lombard speech," *The Journal of the Acoustical Society of America*, vol. 142, no. 2, pp. 493-503, 2017.

[11] P. Tang, I. Yuen, N. Xu Rattanasone and K. Demuth, "Acoustic realization of Mandarin neutral tone and tone sandhi in infant-directed speech and Lombard speech," *The Journal of the Acoustical Society of America*, vol. 142, no. 5, pp. 2823-2835, 2017.

[12] D. Mirman, *Growth Curve Analysis and Visualization using R*. Boca Raton, FL: Chapman & Hall/CRC. 2014

[13] D. Bates, M. Maechler, B. Bolker and S. Walker, "R package version lme4: linear mixed-effects models using Eigen and S4," *Journal of Statistical Software*, vol. 1, no. 7, pp. 1-23, 2014.

[14] A. Kuznetsova, P. B. Brockhoff, R. H. B. Christensen, "lmerTest: tests in linear mixed effects models. R package version 2.0-20," Vienna: R Foundation for Statistical Computing, 2015.

[15] R. V. Lenth, "Least-squares means: the R package lsmeans," *Journal of Statistical Software*, vol. 69, no. 1, pp. 1–33, 2016.

[16] A. Sharma, P. M. Gilley, M. F. Dorman and R. Baldwin, "Deprivation-induced cortical reorganization in children with cochlear implants," *International Journal of Audiology*, vol. 46, no. 9, pp. 494-499, 2007.

[17] L. Liu and R. Kager, "Perception of tones by infants learning a non-tone language," *Cognition*, vol. 133, no. 2, pp. 385-394, 2014.

[18] J. Tan, R. Dowell, & A. Vogel, "Mandarin lexical tone acquisition in cochlear implant users with prelingual deafness: A review". *American Journal of Audiology*, vol. 25, no. 3, pp. 246–256, 2016.