The Representation of Tone Sandhi by Children with Cochlear Implants

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ABSTRACT

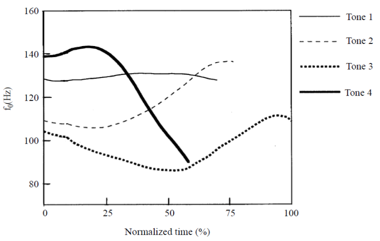
Children with cochlear implants (CIs) face challenges in acquiring tones, as CIs do not transmit pitch information effectively. In connected speech, tones undergo modification, known as tone sandhi processes. In Mandarin, tone sandhi changes the realization of tone 3 (T3) across tonal contexts, resulting in allophonic variants. Previous studies have shown that normal hearing (NH) 3-year-olds correctly produced T3 variants in appropriate sandhi contexts, while children with CIs cannot do so unless implanted early. However, it was unclear whether they have the correct representation of T3 variants. This study examined the T3 representations of 46 children with CIs (implanted from 1 to 5 years) using a mispronunciation paradigm with novel compounds. The results showed that all children with CIs face challenges in recognizing and processing lexical tone as well as tone sandhi words. The implications for future studies are discussed.

Keywords: Children with cochlear implants, Mandarin tones, tone sandhi, speech perception.

1. INTRODUCTION

Cochlear implant (CI) technology has made oral speech communication possible for children with hearing impairment, but it is still challenging for them to learn to tonal languages, since CIs do not transmit pitch information effectively [15]. Mandarin Chinese has four lexical tones, primarily contrastive in pitch contours, i.e., level tone 1 (T1), rising tone 2 (T2), dipping tone 3 (T3) and falling tone 4 (T4). Lexical tones are acquired early by children with normal hearing (NH), i.e., before age 3 [12].

Figure 1: Pitch contours of Mandarin lexical tones.



For children with CIs, acquiring typical lexical tones is challenging, especially for **T2** and **T3**, but early implantation usually leads to better outcomes [3, 4, 7, 11, 13]. For instance, [13] compared the acoustic features of lexical tone productions for 3-7-year-old children with CIs and NH 3-year-olds. It was found that only those implanted before 2 years produced target-like pitch contours for lexical tones. The other children produced much flatter and less distinguishable pitch contours, especially for T2 and T3, suggesting that early implantation is critical for the acquisition of typical lexical tones.

In daily conversation, however, people use connected speech, where lexical tones undergo tonal changes known as tone sandhi processes [3]. The most well-studied tone sandhi process in Mandarin Chinese is T3 sandhi (hereafter "tone sandhi"). Depending on the following lexical tones, tone sandhi processes modify the surface realization of T3 syllables, generating two allophonic variants [3]. In a T3+T3 sequence, where full sandhi occurs, the initial T3 is realized as the rising tone similar to T2 (referred to as *T2 to differentiate it from the underlying lexical T2): T3+T3 → ***T2**+T3. In a T3+T1/T2/T4 sequence, where half sandhi occurs, T3 is realized with a low-falling contour (referred to as half-T3): T3+T1/2/4→**half-T3**+T1/2/4.

It has been shown that Mandarin-speaking NH children have mastered the tone sandhi process before age 3 [12]. Using a novel word formation task, [12] examined NH 3-5-year-olds' productions of novel tone sandhi compounds, e.g., "ma3 gu3" *horse-drum*. The results showed that all child groups correctly produced both allophonic variants of T3 in appropriate sandhi contexts, i.e., ***T2** before T3 and **half-T3** before T1/2/4, suggesting that 3-year-olds have already developed a good understanding of the allophonic variants of T3 and can use them productively in tone sandhi processes.

For children with CIs, correctly producing the allophonic variants of T3 in appropriate sandhi contexts is challenging; they generally produced invariant T3 with level pitch contours across contexts [13]. However, it was unclear whether they represent both allophonic variants of T3 in their mental lexicon. Moreover, it has been found that children implanted before age 2 were able to correctly produce both variants of T3 in appropriate contexts [13]. This raises the question of whether T3 is represented differently for children with different implantation ages. To further explore these issues, it is therefore necessary to extend the investigation of the acquisition of tone sandhi from speech production to speech perception, examining the representation of allophonic variants of T3 in children with CIs.

A recent study tested the representation of allophonic variants of T3 resulting from tone sandhi in NH 3-5-year-olds [14], using intermodal preferential looking (IPL) task [6]. In [14], NH 3-5-year-olds were presented with a pair of pictures, illustrating a sandhi object (novel T3T3 compound), i.e., "ma3 gu3" *horse-drum*, and a novel distractor. An audio stimulus was played with either ***T2**T3 target sandhi tones, or **half-T3**T3 mispronunciations. The results showed that NH children, as well as adult controls, accepted both pronunciations as possible surface realizations for underlying T3T3 items, indicating that both T3 variants were accessed in recognizing T3 syllables in novel tone sandhi compounds. Thus, both variants (***T2** and **half-T3**) are represented in NH 3-5-year-olds' mental lexicon, together under the same abstract T3 category. This raises the question of whether children with CIs represent allophonic variants of T3 in the same way.

The aim of the present study was therefore to examine the perceptual representation of the allophonic variants of T3 resulting from tone sandhi processes in children with CIs. Using a procedure similar to that used in [14], we asked if children with CIs would accept both **half-T3**T3 'mispronunciation' and target ***T2**T3 forms for novel T3T3 compounds, as NH children did. Based on previous findings that early implanted children used both variants of T3 in production [13], we predicted that they might also accept both pronunciation variants in perception, while those with later implantation will only accept ***T2**T3. Moreover, we also included T2T1 non-sandhi (no sandhi processes involved) control items, with **half-T3**T1 mispronunciations. We expected that NH and CI children would reject these non-sandhi **half-T3**T1 mispronunciations.

Given previous findings that children with CIs have problems in acquiring T2 and T3 [11], it is also possible that they might not detect the acoustic changes between correct pronunciations and mispronunciations. Therefore, we also included non-sandhi **T2**T1 compounds as control items (with **half-T3**T1 mispronunciations), where the target and mispronounced syllable 1 was acoustically identical to the sandhi items, but where no sandhi process was involved. We predicted that children implanted later would show difficulties in detecting the tonal changes mispronunciations in the control condition.

2. METHODS

2.1. Participant

Forty six 3-7-year-old (mean age: 4;11; SD: 10.4 months) Mandarin-speaking children who are prelingually deaf were recruited from rehabilitation centres/regular preschools in Beijing, China. Thirty-two 3-year-old NH controls (NH=3) were included as controls, because they have already acquired tone sandhi [12-13]. Based on the age at implantation of children with CIs, they were grouped into four groups: 1-2 years (CI_Imp 1-2: 5 children); 2-3 years (CI_Imp 2-3: 20 children); 3-4 years (CI_Imp 3-4: 14 children); and 4-5 years (CI_Imp 4-5: 7 children). The study was conducted in accordance with the ethics protocol approved by Macquarie University's Human Ethics Panel.

2.2. Stimuli

Two types of disyllabic "animal + object" novel compounds were used as stimuli, including eight *non-sandhi* T2T1 control items, e.g., "niu2 deng1" *cow-bulb*, and eight *tone sandhi* (underlying T3T3) target items, e.g., "ma3 gu3" *horse-drum*, with the surface realization ***T2**T3. Tonal mispronunciations were obtained by changing the target syllable (underlying T2 and surface *T2) to **half-T3** using the same method as that used in [14], resulting in eight *non-sandhi* and eight *sandhi* mispronunciations (Table 1).

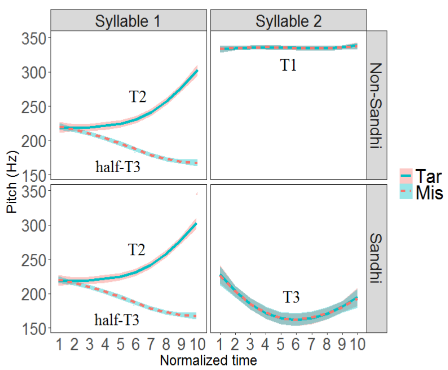
Table 1: Novel compound tonal stimuli.

	Non-sandhi (underlying T2T1)	**Sandhi** (underlying T3T3)
Target surface tones	**T2**T1	***T2**T3
Mispronounced surface tones	**half-T3**T1	**half-T3**T3

2.2.1. Audio stimuli

Speech stimuli were recorded by a female Beijing-Mandarin speaker. Mispronunciations were made via replacing the pitch of the target T2/*T2 syllables with that of half-T3 syllables, using the Praat software [1]. The Syllable 1 non-sandhi control target and mispronounced tones are acoustically identical to the target and mispronounced sandhi forms. Thus, any differences between the two conditions would be due to phonological, not phonetic, differences.

Figure 2: Pitch contour of stimuli (Tar = Target; Mis = Mispronunciation).



2.2.2. Visual stimuli

Each audio stimulus was matched with a pair of yoked familiar vs. novel pictures. For instance, the familiar picture for "ma3 gu3" *horse-drum* illustrates a drum with a horse on it, was yoked to a novel picture illustrating a drum with a novel animal on it.

2.2.3. Apparatus

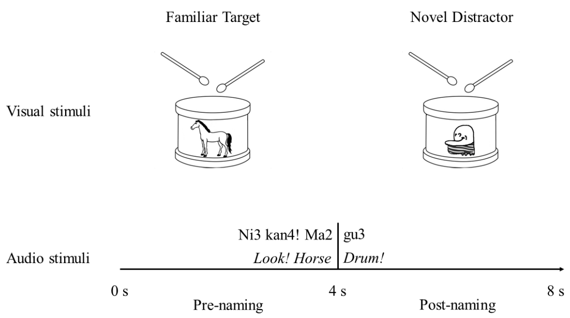
Audio stimuli were played via speakers/headphones at 70 dB SPL. The SMI Red-250 portable eye-tracker was used to record participants' visual fixations with a 9-point calibration procedure prior to testing.

2.2.4. Procedure

All participants were tested in quiet rooms. Prior to testing, a picture naming task had been conducted to ensure that all participants knew the underlying tone of each word used to form the novel compounds in the perception experiment (cf. [12]).

The procedure of the perception experiment was identical as that used in [14], i.e., three practice trials followed by 19 test trials. Within the 19 test trials, there were three *word*-mispronunciation trials (where Syllable 1 was replaced with a syllable that differed from the target in both segments and tone), used as a screener to exclude any participant who did not understand the task (see the exclusion section below).

Figure 3: Sequence of events in each trial.



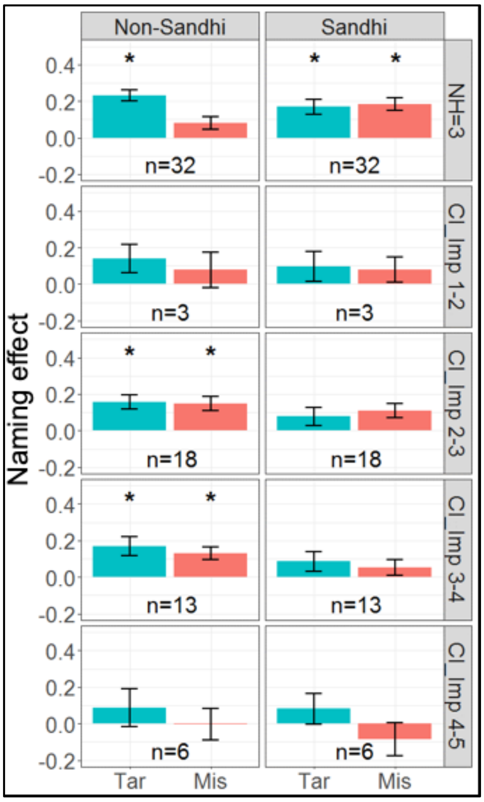
2.3. Data analysis

For each trial, the **naming effect** of looks to the familiar picture was measured, calculated as the difference of looks to the familiar target between *pre-* and *post*-naming phases. A total of 1248 trials were obtained. Participants were then screened using the three word-mispronunciation trials, for which we expected *negative* naming effects in at least two trials. Six children with CIs were excluded from further analysis for not reaching this criterion. In addition, 87 trials with greater than 50% track-loss were then also excluded, resulting in a total of 40 children with CIs (553 trials) and 32 NH 3-year-olds (512 trials) included in the final analysis.

3. RESULTS

Figure 4 illustrates the naming effect of looks to the familiar picture across conditions. A series of one-sample *t*-tests (with Bonferroni adjustment) were computed to compare the naming effects to baseline (naming effect = 0). The results showed that the NH=3 looked to target pictures in three conditions: non-sandhi, sandhi correct and sandhi mispronunciations (Figure 4). However, children with CIs generally did not look to either familiar or novel picture upon hearing the audio stimuli, except for the CI_Imp 2-3 and CI_Imp 3-4 groups in the non-sandhi conditions. This result suggests that NH children accepted non-sandhi and sandhi correct pronunciations and sandhi mispronunciations, but most CI groups (even the few with early implantation) did not associate the audio stimuli with the visual objects. This indicates that children with CIs could not identify correct productions of the lexical tone and tone sandhi words.

Figure 4: Naming effects across groups and conditions (Tar = Target; Mis = Mispronunciation; n = Number of participants).



A linear-mixed effects model was performed to compare the naming effect between the *correct* and *mispronunciation* trials across conditions and groups, with three fixed factors "Groups" (NH=3, CI_Imp 1-2, CI_Imp 2-3, CI_Imp 3-4 and CI_Imp 4-5), "Condition" (Non-Sandhi and Sandhi) and "Pronunciation" (Target and Mispronunciation), and a random intercept "Participant". The results produced a significant interaction of “Group × Condition × Pronunciation” (F (4, 538) = 2.48, $p < 0.05$. The results of the post-hoc test showed that, in the **non-sandhi** control condition, relative to the target pronunciation, NH 3-year-olds looked significantly less to the target picture when hearing the mispronunciations (β = 0.15, SE = 0.07, $t(536)=1.97$, $p<0.05$). However, CI groups did not show any difference of looking between target pronunciation and mispronunciation trials. This indicates that children with CIs, including those with early implantation, did not detect the tonal changes between correct and mispronunciations even in the control condition.

4. DISCUSSION

The present study examined the representation of allophonic variants of T3 in children with CIs using the IPL paradigm. The results showed that NH children accepted both *T2T3 target pronunciations and half-T3T3 mispronunciations for underlying T3T3 compounds, indicating that they had accessed both ***T2** and **half-T3** in processing novel T3 words in the tone sandhi context, and have the representation of both T3 variants in their mental lexicon. However, the result of children with CIs differed from that of NH children in two aspects. First, most CI groups, including those with early implantation (before age 2), were not able to associate the audio stimuli with the visual objects; they did not show any preference to either the familiar or novel picture upon hearing the audio stimuli. Second, detecting the T2/*T2 and half-T3 mispronunciation is challenging; none of the CI groups showed a looking difference between the target and mispronunciation trials. Thus, it remains unclear when and how allophonic variants of T3 are lexically represented in children with CIs.

The poor performance of associating the audio stimuli to the target picture by children with CIs might be related to the task used in this study, i.e., novel word recognition. It has been well-documented that children with CIs exhibit difficulties in learning new words, performing poorly in building word-object associations during word learning [5, 8-10]. This is because (a) the auditory information provided by CIs is impoverished and highly degraded, and (b) the period of early sensory deprivation prior to implantation may lead to a delayed and/or disordered course of language development [5, 8-10]. In the present study, our task required children to recognize novel compounds that they have never heard before, and link these words to novel pictures. This task might require a high word-learning and phonological processing ability, which is limited for children with CIs, resulting in their inability to perform the task.

Another challenge that children with CIs faced in this experiment was to detect the tonal mispronunciation between T2/*T2 and half-T3. Previous study reported that children with CIs find differentiating between T2 and T3 challenging [11]. This is because the pitch contours of T2 and T3 are very similar, and correctly differentiating between them requires the detection of subtle pitch contour difference using fine-grained pitch information, which is severely degraded in CI devices [15]. This also indicates that these children face challenges in building robust representations of T2 and T3.

One of the central questions we asked is whether early implantation would benefit children with CIs, helping them develop typical phonological representations of allophonic variants of T3. Thus, we expected that the early implanted group might perform like NH children, rejecting the tonal mispronunciation in the control condition but accepting it in the sandhi condition. However, the results did not show this pattern, with no preference for either the target picture or other picture upon hearing the audio stimuli. This might be related to the insufficient number of participants in the early implantation group, i.e., only five early implanted children were initially tested and only three included in the final analysis after exclusion based on performance of the three *word*-mispronunciation trials. Therefore, based on the current study, it is hard to draw a strong conclusion regarding the effect of early implantation of the development of T3 representations.

Nonetheless, our study has implications for future research to further explore this issue. First, given the insufficient number of participants in the critical early implantation group, it is necessary in future studies to test more children with early implantation, i.e., implanted before age 2 or even age 1, to gain a deeper understanding of the effect of early implantation on the development of tonal representations. Second, given these children’s poor ability in recognizing and processing novel compounds, it will be helpful in future studies to test their performance on familiar/lexicalized tone sandhi words, i.e., ‘yu3 san3’ *umbrella*, like what has been done in the study of [16] on NH children, which might require less processing effort for children with CIs.

In summary, the current study examined the phonological representation of allophonic variants of T3 from tone sandhi in lexical representations of children with CIs, using the IPL paradigm. The results showed that these children mapped neither the correct nor the mispronunciations to either familiar or novel picture. This indicates that children with CIs face challenges in recognizing and processing new words and detecting tonal changes involving T2 and T3. This suggests that future research could use familiar words, testing greater numbers of early implanted children, to further explore this issue.

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