A Study on the Phonetic Inventory Development of Children with Cochlear Implants for 5 Years after Implantation

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Abstract
This paper investigates longitudinal phonetic inventories of vowels and consonants of Korean-speaking children with cochlear implants (CIs). They are based on speech data of 7 children with CI over 5 years PI to examine the entire speech production development. Phones produced at least twice by more than 50% children in spontaneous and imitation speech from 6 months to 5 years post-implantation (PI) are compiled in the inventories. The results show and differences and similarities between children with CI and with normal hearing (NH). The vowel and consonant inventories at 6 months PI are larger than those of NH children at 1 year of age whose hearing experience is longer, including liquid [ɾ] and fricative [s]. It can be attributed to biological maturation of CI children. As in children with NH, there is an explosive increase in phonetic inventories during a year after 1-year of robust hearing experience and the inventories are almost complete after 3 years of PI. Phonetic inventories at each time are expected to be references to assess the developmental appropriateness in speech production and guides to direct habilitation goals.

Index Terms: phonetic inventory, speech production, cochlear implant, speech corpus

1. Introduction
A cochlear implant (CI) is a “small and complex electronic device that can help to provide a sense of sound to a person who is profoundly deaf or severely hard-of-hearing” according to [1]. The inserted CIs stimulates the auditory nerve in the cochlea to convey sound signals to the brain, by bypassing the damaged parts of the inner ear. However, hearing through a CI is not the same as normal hearing and it takes time for a person with CIs to learn or relearn hearing. People with CIs take advantage of improved speech perception, followed by better speech and language skills [2, 3].

The number of younger children who are deaf or hard-of-hearing and benefitting from CI continues to increase, but their speech development still lags behind normal hearing (NH) children who are at the same chronological age [4, 5, 6]. In addition, children with CI are reported to have problems in speech production. For example, Korean children with CI produced fricatives and liquids less accurately [7, 8, 9, 10] and made idiosyncratic phonological errors and more developmental phonological errors [7, 8].

In order to investigate speech production development, a phonetic inventory is conducted by listing sounds produced by a child without considering correctness [11, 12, 13, 14]. A phone which occurs in more than two tokens by more than 50% of children is included into the inventory in general [11, 14, 15]. As a phonetic inventory reveals both sounds which a child produces and does not produce [12, 16], it is important in clinical settings with children with CI. Based on the phonetic inventory of each child, the clinician in charge can evaluate the development of the child’s speech production [17] and set the treatment goals [18]. It can be compared with those obtained from NH children with comparable robust hearing experience [14]. Robust hearing experience indicates “the amount of time a child has had auditory access to speech at conversational levels” according to [19].

Longitudinality is one of the significant properties of studies on a phonetic inventory. Speech analyses on English-speaking children with CI are conducted to encompass longitudinal development of speech production [20, 21, 22, 23, 24]. In particular, [22, 23] investigated phonetic inventories over 6 years after implantation, providing complete vowel and consonant inventories. However, in studies providing phonetic inventories of Korean-speaking children with CI [8, 25, 26], the duration of study is not long enough for the phonetic inventories to include the phones which emerge at the early period [26] or to be completed [8, 25]. Phonetic inventories showing the entire speech production development of children with CI are in need to be used as norms for speech production evaluation of a child with CI and help clinicians to provide treatment feedback. Because of the long period of study, studies providing a phonetic inventory of children with CI generally analyze speech from the small number of participants such as 5 to 10 children with CI [20, 21, 22, 23, 25]. Some studies analyzed 10 to 15 children with CI [14, 24], and some studies with additional purposes included more than 15 [8, 26].

This paper investigates the vowel and consonant phonetic inventories development of 7 children with CI over 5 years post-implantation (PI) for the first time. The rest of the paper is constructed as follows. The next section presents the related studies on phonetic inventories of Korean-speaking children with NH and CI. Section 3 explains the corpus used for the analysis and the detailed method for compiling the phonetic inventories. It is followed by the development of phonetic inventories during a period of 5 years after implantation in Section 4. Section 5 summarizes and discuss the results. Section 6 provides the conclusion and direction of future work.

2. Background and related works
The Korean phoneme system is composed of 7 monophthongs, 10 diphthongs, 18 word-initial consonants, and 7 word-final consonants [27, 28]. Korean vowels and consonants in IPA are as below:

- Monophthongs: i, ɨ, ʌ, ɑ, o, u, ɯ
- Diphthongs
o with semivowel [j]: je, jα, ja, ju, jo
o with semivowel [w]: wi, wα, wa
o with semivowel [u]: uι

• Word-initial consonants: b, p, b̌, b, t, ǩ, k, ď, ť, w, s, h, m, n, r

• Word-final consonants: p, t, k, m, n, η, l

Few studies examined the Korean vowel inventory of NH children. [29] provided a vowel inventory of phones produced at least 3 times by more than 50% of 53 infants. The inventory at 6 months included [a, e, u], and more monophthongs [α, i, u] were added at 18 months. Around 24 months, all monophthongs, and a diphthong [ju] were produced. It indicates that vowels with roundedness and diphthongs are produced later.

Studies providing the Korean consonant inventories of NH children younger than 2 years included phones produced at a varied frequency; more than 3 times [29]; more than twice [15]; or at least once [30]. The word-initial consonant inventories are presented in Table 1, and the word-final consonant inventories in Table 2. Despite the differences in the inclusion criterion of phones and subjects, they show common patterns in children’s word-initial consonant inventories. The bilrabal consonant [m] was the earliest one included by 12 months. The largest increase in the number of phones entering the inventories was observed during the period from 12 to 24 months. The development of word-final consonants was not consistent except for the fact that nasal consonants emerged earlier than others.

[31] investigated 2 to 6 years-old NH children’s percentage of correct consonants and provided developmental changes of the children’s consonant production. Before the age of 3, more than 50% of the children could correctly produce all word-initial and word-final consonants except for alveolar fricatives [s, s']. Every consonant could be correctly produced by more than a half of the 3-year-old children.

For the Korean children with CI, early phonetic inventories after implantation were analyzed. Vowel inventory was established in [25, 26]. [25] examined speech from the children with CI who got implanted before 18 months, for 9 months with 3-month intervals. During the first 9 months of using CI device, 2 out of 3 children produced every monophthong. Diphthong [wa] was produced at 6 months of PI, and [ja, jα] by 9 months of PI. [26] provided the inventories for 4 years, composed of phones produced more than twice by more than 50% of 16 children in imitation speech using a speech corpus of children with CI who received implantation before the age of 3. Every monophthong except [α] was included in the inventory at 1 year of PI. By 2 years PI, all monophthongs were added. Diphthongs were not analyzed.

Table 1: Word-initial consonant inventories from previous studies on children with NH

<table>
<thead>
<tr>
<th>Word-initial consonant inventory</th>
<th>1:0 [29]</th>
<th>1:6 [29]</th>
<th>2:0 [29]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>m</td>
<td>m b p</td>
<td>m b p</td>
</tr>
<tr>
<td>1:0 [29]</td>
<td>m</td>
<td>m b p</td>
<td>m b p</td>
</tr>
<tr>
<td>1:6 [29]</td>
<td>[30] g</td>
<td>[30] g</td>
<td>[30] g</td>
</tr>
<tr>
<td></td>
<td>m p* s</td>
<td>m p* s</td>
<td>m p* s</td>
</tr>
<tr>
<td>produced in front of the vowel [j]</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
k̚) and [g, h] were added at 1- and 2-years PI, respectively. After a year, [s̚] was added and every word-initial consonant except [r̚] was produced. The word-final consonant inventory after 6 months of implantation included [k̚, t̚, m, p̚], but no more consonants were added at 1-, 2-, and 3-years PI.

The word-initial consonant inventories from [8, 25, 26] are summarized in Table 3, and the word-final consonant inventories in Table 4. All studies [8, 25, 26] on phonetic inventories of children with CI showed common patterns: monophthongs were produced within 1 year of hearing experience and diphthongs were produced later than monophthongs; biliteral consonants were one of the earliest consonants in word-initial and word-final positions; many consonants started to be produced during 1 to 2 years after implantation; [r̚] and [s̚] were produced latest. However, they did not also cover every significant time point for analyzing speech such as 6 months PI [26], or the last period of speech production development [8, 25], leading to no reliable longitudinal phonetic inventories for Korean children with CI.

3. Method

3.1. A corpus of children with CI

A speech corpus of children with CI was created to analyze their speech and language characteristics, and to be used as a resource to develop a habilitation program for speech production. The audio recordings of children with CI were provided from a speech and language therapy center in otolaryngology in the Seoul National University Hospital in Seoul, Korea. The children had their first implantation before the age of 3 and were reported by their caregivers that they have no additional disorders nor cerebral anomalies. No additional information about the children, their CI devices, and habilitation except for the duration of robust hearing is included in the corpus.

Each child was recorded during speech and language therapy or evaluation sessions for at least 4 years after implantation. The evaluation sessions are typically held annually in addition to 6 months and 1 and a half years PI, which results in recordings at 0, 6 (years;months), 1, 1, 1, 2, 3, 3, 4, 5, 5 years after implantation. The speech data is composed of spontaneous speech during conversation and imitation speech from various speech, language, and speech perception assessments, including monosyllabic words, bisyllabic nonsense words (e.g. /hVdu/ with a monophthong, /aCa/ with C a word-initial consonant), bisyllabic words, clauses, and sentences. The speech corpus will be expanded with more speech data from more than 20 children with CI.

Every utterance is orthographically transcribed in the Korean alphabet, Hangeul. If an utterance is judged to have one or more mispronunciations by the first author, who has a national certificate of speech and language pathology, a phonetic transcription in the Korean alphabet and phonological error patterns of the target phoneme are additionally annotated. The total number of analyzed utterances is 6,451.

3.2. Compiling phonetic inventories

A vowel inventory, a word-initial consonant inventory, and a word-final consonant inventory are established at each time point. Vowels include monophthongs and diphthongs. Phones produced at least twice by more than 50% of 7 children with CI are included, which is in accordance with previous studies on establishing a phonetic inventory of NH children [11, 12, 13, 15] and children with CI [14, 22, 23]. The time points for compiling phonetic inventories cover 0:6, 1:0, 1:6, 2:0, 3:0, 4:0, and 5:0 years of PI to investigate the entire period for phonetic development of children with CI. The 6-month intervals until 2:0 years PI is set to examine early phonetic inventories. For the utterances judged to be correctly pronounced, the orthographic transcription is converted to phonetic transcription. A Korean grapheme-to-phoneme toolkit on Python, g2pk [32], is used for the conversion. As utterances judged to have mispronunciations are phonetically transcribed in the Korean alphabet, the phonetic transcription is used.

4. Results

4.1. Vowel inventory

The vowel inventory is presented in Table 5. Phones included in the inventory for the first time are in bold. The vowel in brackets represents that it is not included in the inventory until 5 years PI. All 7 monophthongs and 2 monophthongs are produced at 6 months PI. The diphthong inventory gradually increases and all diphthongs except for [ui̯] are included by 4 years of PI.

<table>
<thead>
<tr>
<th>Vowel Inventory</th>
</tr>
</thead>
<tbody>
<tr>
<td>0:6 a a e o u w i ja js</td>
</tr>
<tr>
<td>1:0 a a e o u w i ja js</td>
</tr>
<tr>
<td>1:6 a a e o u w i ja js je jo</td>
</tr>
<tr>
<td>2:0 a a e o u w i ja js je jo wa we</td>
</tr>
<tr>
<td>3:0 a a e o u w i ja js je jo wa wa wa</td>
</tr>
<tr>
<td>4:0 a a e o u w i ja js je jo wa wa wa wi</td>
</tr>
<tr>
<td>5:0 a a e o u w i ja js je jo wa wa wa wi [ui̯]</td>
</tr>
</tbody>
</table>

4.2. Consonant inventory

4.2.1. Word-initial consonant inventory

The word-initial consonant inventory is described in Table 6. Phones included in the inventory for the first time are in bold. Stop consonants at all places of articulation [g, k̚, d, t̚, b, p̚] and other consonants such as [m, n, r̚, s̚] are included at 6 months PI. By a year of PI, [h] is added, which is followed by [de, teh, p̚, t̚, b̚, k̚] at 1:6 years PI. At 2 years PI, [w̚] is included. After 3 years of robust hearing experience, the inventory is completed by adding [s̚].

<table>
<thead>
<tr>
<th>Word-initial consonant inventory</th>
</tr>
</thead>
<tbody>
<tr>
<td>0:6 g k̚ n d t̚ m b p s</td>
</tr>
<tr>
<td>1:0 k̚ n d t̚ m b s</td>
</tr>
<tr>
<td>1:6 g k̚ n d t̚ m b p̚ s dh teh k̚ t̚ p̚ h</td>
</tr>
<tr>
<td>2:0 g k̚ n d t̚ m b p̚ s dh teh w̚ t̚ k̚ t̚ p̚ h</td>
</tr>
<tr>
<td>3:0 g k̚ n d t̚ m b p s s̚ dh teh w̚ t̚ k̚ t̚ p̚ h</td>
</tr>
<tr>
<td>4:0 g k̚ n d t̚ m b p̚ s s̚ dh teh w̚ t̚ k̚ t̚ p̚ h</td>
</tr>
<tr>
<td>5:0 g k̚ n d t̚ m b p̚ s s̚ dh teh w̚ t̚ k̚ t̚ p̚ h</td>
</tr>
</tbody>
</table>

4.2.2. Word-final consonant inventory

The word-final consonant inventory is described in Table 7. Phones included in the inventory for the first time are in bold. The inventory contains all word-final consonants except for [k̚] at 0:6 years of PI. [k̚] is added at 2:0 years of PI, which completes the inventory.
Table 7: Word-final consonant inventory

<table>
<thead>
<tr>
<th>Word-final consonant inventory</th>
</tr>
</thead>
<tbody>
<tr>
<td>0;6</td>
</tr>
<tr>
<td>1;0</td>
</tr>
<tr>
<td>1;6</td>
</tr>
<tr>
<td>2;0</td>
</tr>
<tr>
<td>3;0</td>
</tr>
<tr>
<td>4;0</td>
</tr>
<tr>
<td>5;0</td>
</tr>
</tbody>
</table>

5. Discussion

This paper examines voice and consonant inventories development of children with CI during 5 years after implantation. After 6 months PI, the phonetic inventories contain various phones including 9 vowels, 10 word-initial consonants, and 6 word-final consonants. The inventories increase dramatically during a period of 1 year after having 1 year of robust hearing experience. The vowel inventory is almost complete at 4 years PI. The inventory of consonant in word-initial position is complete at 3 years PI, and for word-final position is complete at 2 years PI.

The size of inventories at 6 months PI as seen in Table 8 and 9 is larger than that of NH children with more robust hearing experience in Table 3 and 4 [29, 30]. It could be attributed to biological maturation of children with CI. Children with CI at 6 months PI are much older than NH children at 1 year since children with CI had the implantation after 1 year of chronological age, which results in more skillful movement of articulators.

It is noteworthy that fricative [s] and liquid [ɾ] are included into the inventory since 6 months PI. The production of [s] is earlier than children with NH [31] and with CI [8, 26]. The early production of [s] would be a unique pattern for children with CI considering English-speaking children with CI produced it early, by 15 months PI [14]. Liquid [ɾ] occurred in children with NH at the age of 2.0 [15, 30] and later than 4.0 PI in children with CI [8, 26]. The early production of [ɾ] could be related to the type of speech. For younger infants with CI, most audio recordings are phonation or babblings and transcribed perceptually.

The explosive expansion of phonetic inventories during 1 year after 1-year PI is consistent with children with NH [15, 29, 30] and CI [8, 25, 26] who have similar robust hearing experience. It implies that 1 to 2 years after implantation is a critical period for speech production development. Other common developmental patterns with NH children include the late production of vowels with roundedness [29], the first production of bilabial consonants [15, 29, 30], and the late production of the alveolar fricative [s] [31].

The vowel inventory is not complete until 5 years PI. It is explained by the low occurrence frequency of the diphthong [ui]. Nonetheless, all monophthongs are produced at 0.6 years PI, which is earlier than [25, 26]. Most word-initial consonants are included in the inventory after 3 years of robust hearing experience as in studies on children with NH [31] and CI [8, 26]. The word-final inventory is complete after 2 years with robust hearing experience, which is earlier than [26] and later than [8]. The reason for the more rapid speech production development than [26] is speculated that [26] only analyzed imitation speech, which led to less utterances. The slower development than [8] could be attributed to the broader inclusion criterion of 25% children in [8] than 50% children in this paper.

There is variability among individual child though individual phonetic inventories are not present here. Some children show slower development than others. For example, among 6 children with audio recordings at 6 months PI, 3 produce all monophthongs, 2 produce all unrounded ones, and one produces all unrounded ones except for [ui]. Children with earlier vowel production produce diphthongs earlier than others. However, a child shows quite a different pattern. Only one vowel [i] is produced at 1-year PI and 2 vowels [a, e] are additionally produced at 1.6 years of PI. The monophthong inventory is complete at 2.0 years, catching up with others. Similar patterns are applied to consonant inventories as well. Some children produce all plosives from 0.6 years PI, while others start to produce all of them at 1.6 years. Children with later vowel production tend to produce consonant later.

One of the limitations of this study is that, due to the lack of information about the children with CI in the corpus, it is impossible to analyze the speech production development with respect to influential factors such as chronological age, information about hearing loss, speech perception skills, and CI devices and speech processing strategy. It should be dealt with in detail when the information in need is appended as metadata in the speech corpus.

6. Conclusions

This paper investigates phonetic inventories of vowels and consonants of 7 Korean-speaking children with CI over 5 years PI to examine the entire speech production development. The results are compared with those of children with NH and CI in previous studies, showing differences and similarities. The phonetic inventories at 6 months PI are larger than those of NH children at the age of 1 thanks to biological maturation. There is an explosive increase in phonetic inventories during a year after 1-year of robust hearing both in children with NH and CI. The inventories are almost complete with 3 years of robust hearing experience as in NH children.

In the future, more speech data from other children with CI should be analyzed to represent their speech production skills. Information related to speech production development should be considered to deeply understand the development of phonetic inventories of children with CI. In addition, speech error patterns should be analyzed to completely shed light on characteristics of speech production of children with CI.

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8. References


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