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인공와우 이식 시기에 따른 한국 청각장애아동의 말소리 명료도 변화

Changes in Speech Intelligibility of Korean Hearing-impaired Children in relation to Age at Cochlear Implantation

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Purpose: Hearing-impaired children with cochlear implants (CIs) show improvement in their speech recognition ability over their period of wearing. The purpose of this study is to examine the effect on the children's speech intelligibility of the age at which they received the implants. **Methods**: Ten hearing-impaired children who received cochlear implants before or after they reached 6 years of age participated in the study and, as a control group, five normal hearing children also participated. A CSL 4500 by Kay Corp. was used to analyse the phonetic characteristics of Korean phonemes; samples of vowels /ɑ/, /i/ and /u/ of individual groups were collected and the values and rates of F1 and F2 of vowel were analysed. To process resultant data, one-way ANOVAs were conducted. **Results**: The results indicated that the hearing impaired children who received cochlear implants after 6 years of age were significantly higher in F1 and F2 than children who were deaf and hearing impaired children before 6 years of age. In the vowel /i/, similar results were obtained in F1. The hearing impaired children who had cochlear implants before 6 years of age did not show any significant difference from the vowels of the hearing impaired children. **Conclusions**: It could be seen that age of cochlear implantation affected hearing-impaired children's speech intelligibility. It is effective to receive a cochlear implant before 6 years of age to improve the speech clarity of the hearing impaired child.

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목적: 인공와우 이식한 청각장애아동은 인공와우 착용 기간에 따라 말지각력이 향상된다고 많은 선행연구에서 보고되고 있다. 이에 본 연구에서는 인공와우를 착용한 시기에 따라 청각장애아동의 한국 말소리 명료도의 변화를 살펴보고자 하였다. **방법**: 인공와우 수술을 받은 시점을 중심으로 만 6세 전후로 나누어 청각장애아동 2집단을 분리하였고, 통제집단으로 6세 건청아동으로 하였다. 대상자들의 자발적인 발성을 위해 발음오류가 적은 모음 /아/, /이/, /우/를 산출하게 하였으며, 모든 음성은 CSL(Model CSL 4500, Kay사)을 활용하여 표본추출률 22000Hz에서 수집하여 wav 파일로 저장하였다. 각 모음별 F1와 F2 음형대를 분석하여 모음삼각도를 살펴보았다. 결과자료는 일변량 분산분석으로 처리하였다. **결과**: 모음 /아/에서 6세 이후에 인공와우이식받은 청각장애아동들의 F1과 F2는 6세 이전에 인공와우 이식한 청각장애아동과 건청아동보다 유의하게 높았다. 모음 /이/에서는 F1에서 이와 유사한 결과가 나타났다. 6세 이전에 인공와우 이식한 청각장애아동은 건청아동의 모음 음형대와 유의한 차이가 나타나지 않았다. **결론**: 외국인청각장애아동의 말소리 명료도는 인공와우 이식시기가 중요하며, 이를 향상시키기 위해 가능한 6세 이전에 인공와우 이식술을 받는 것이 효과적임을 알 수 있다.

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Ⅰ. Introduction

Generally, hearing-impaired children (HIC) produce much less clear articulations compared to normal hearing children (HC). Hearing-impaired children who cannot hear sounds have difficulties in perceiving their mis-articulations and have limitations in receiving others' messages. As a result, hearing-impaired children come to phonate through the feedback of their resonance system and this phonation produces the inappropriate articulations that accompany distortion, resonance disorders or voice disorders(Andrews, 2006). The levels of hearing-impaired children's speech intelligibility vary greatly with their hearing loss levels. Children with mild hearing loss show distortions of some phonemes but do not have significant problems in communicating with others. Children with severe hearing loss can hardly hear their own voices or others' voices and thus their interactions between articulation and resonance systems or utilization of the systems are inadequate, leading to mis-articulations. Consequently, those with normal hearing have difficulty understanding those with severe hearing loss. However, if such children receive sufficient auditory compensations, their utilization of their vocal organs will change. The development of phonemes appears as HC grow and when a certain time has passed, phonemes do not develop any further and HC become to be able to accurately produce the articulations of the language used in their society. Even if some phonemes are omitted or replaced by young children, so long as the phonemes steadily develop as the children grow, all phonemes will be established when the children have reached the age of 7 years. As the children grow, their problematic phonemes are corrected when they hear the speech of their parents or others and as they repeat articulations in their own speech trying to produce similar articulations. It is assumed that the phonemes of children with severe hearing loss will vary according to the extent of their deprivation of such correction.

In general, phonemes are analyzed based on spectrograms in order to analyse the intelligibility of articulations. In particular, on analysing the spectrograms of vowels, formants could see clearly. This is because different frequency bands are formed by the movements of the resonance cavity and the articulator(Clark & Yallop, 1995). In the case of hearing-impaired children, the movements of the articulator and the utilization of the resonance cavity become different from those of hearing children due to defects in their auditory feedbacks. To analyse hearing-impaired children's speech intelligibility, their vowels' formants are analysed to figure out their articulation producing patterns(Allen et al., 1998). Would these movements of their articulators be naturally corrected if sufficient auditory compensation is provided to hearing-impaired children? In general, previous studies of hearing-impaired children with cochlear implants (CIs) have reported that these children showed higher speech recognition and auditory performance compared to hearing-impaired children with hearing aids (HAs)(Allen et al., 1998; Gants et al., 1994; Nikolopoulus et al., 1999). Furthermore, it was indicated that in the case of hearing-impaired children with multi-handicaps, emotional stability and communication skills were improved with CIs(Lanson et al., 2007). On reviewing the results of these previous studies, it can be seen that hearing-impaired children with CIs show diverse levels of auditory cognitive abilities and speech recognition abilities due to diverse factors possessed by these children, such as onset time of hearing loss, hearing loss levels, length of time wearing HAs, age at cochlear implantation, periods of wearing assisting devices, parents' attitudes and individuals' histories (Estabrooks & Oliver, 2002; Lanson et al., 2007; McDermott, 1998; Niparko et al., 2000; Tyler, 1994).

In some studies where child's age at implantation was mentioned, it has been reported that CIs were effective for hearing and speech recognition of hearing-impaired children only when CIs were implanted before the children reached 6 years of age, in general based on the analysis of the children's auditory cortex activities(Kang et al., 2004). In Kang's study, it was reported that even children with severe hearing loss could learn languages and recognize the phonetic characteristics of phonemes if they received sufficient auditory stimuli, such that their auditory cortexes were activated, before they reached 6 years of age. It was also reported in the study that after the age of 6 years, the children's auditory cortexes were activated by other stimuli than auditory stimuli and consequently the children were barely able to acquire acoustic characteristics. It was also reported that in the case of hearing-impaired children who received cochlear implants after 6 years of age or when they had reached school age, auditory cortexes responded to other sensory stimuli than auditory stimuli, thereby emphasizing the importance of age at implantation.

However, in previous studies on speech intelligibility, it has been reported that the intelligibility of articulations of hearing-impaired children with CI is improved over the period of wearing cochlear implants(Nikolopoulos et al., 1999). That is, the study reports indicating that the intelligibility of articulations will be steadily improved even if hearing-impaired children are implanted with CIs after they reach the age of 6 years contradicts the reports indicating that if cochlear implants are implanted after hearing-impaired children reach 6 years of age, their auditory cortex regions will be activated together with other sensory organs. Therefore, in the present study, hearing-impaired children who have been implanted with cochlear implants before and after their chronological age reached 6 years and had long hearing experience after the cochlear implantation were selected and the intelligibility of their vowels were examined. In the present study, first, the characteristics of Korean vowels of normal hearing children were examined and then, after analysing the acoustic characteristics of Korean vowels of hearing-impaired children with CI, the characteristics were analysed again in relation to age at cochlear implantation. The present study will present criteria for selecting the subjects of articulatory treatment from cochlear implantees and the results will be provided as basic data for treatment strategies.

Ⅱ. Methods

1. Subjects

This present study was conducted to figure out the effects of age at cochlear implantation on the articulatory abilities of hearing-impaired children with cochlear implants. In the experimental group of this present study, 10 cochlear implanted children participated; of those, five were implanted with cochlear implants before they had reached 6 years of age and the remaining five were implanted with cochlear implants after they had reached 6 years of age. Their mean age was 12.93 years with an SD (standard deviation) of 3.24 years. All of them were selected from children who had been diagnosed early as cognitive hearing-impaired children in Kyungpook National University Hospital and had at least severe hearing loss. They were also communicating with normal people through oral speech and had worn cochlear implants for at least four years, allowing them to sufficiently adapt to cochlear implants. The study subjects consisted of hearing - impaired children wearing cochlear implants for more than 3 years. The reason for this is that Tyler (1996) reported improvement in articulatory clarity when wearing cochlear implants for more than 2 years. None of the children had any secondary disorder. Concrete information on the children is presented in table 1.

Table 1. Demographic data and information for all subjects

Group	Patient	Gender	Age	Age at CI	Duration of CI	Side of CI	Processor	Processing strategy	Mean hearing with CI
NH	N1	M	7						
	N2	M	10						
	N3	M	9						
	N4	F	9						
	N5	F	9						
CI before 6yrs.	HI1	F	7	3	4	Rt	Freedom	ACE	28
	HI2	M	8	3	5	Lt	ESPrit 3G	ACE	27
	HI3	F	8	1	7	Lt	Freedom	ACE	30
	HI4	F	9	2	7	Lt	Freedom	ACE	25
	HI5	F	9	2	7	Lt	ESPrit 3G	ACE	27
CI after 6yrs.	HI6	F	15	8	7	Lt	Med-eL	CIS	25
	HI7	F	16	8	8	Lt	ESPrit 3G	ACE	28
	HI8	F	15	11	4	Rt	Freedom	ACE	28
	HI9	M	12	8	4	Lt	Freedom	ACE	25
	HI10	M	13	9	4	Lt	Clarion	ACE	25

Since the Korean vowel phonetic characteristics of hearing children should be presented to analyse the phonetic characteristics of hearing-impaired children with cochlear implants, five hearing children were selected as a control group. They correspond to N1 through N5 in Table 1. Their mean age was 8.8 years with an SD of 1.1 years. Through physiological tests, children with no observed physiological or pathological problems in their hearing organs, articulation organs, or vocal organs were selected.

2. Procedure

To analyse hearing-impaired children's articulation intelligibility in relation to age at cochlear implantation, vowels that facilitate acoustic analyses based on voluntary vocalizations were selected and examined. In general, vowels form a vowel square diagram based on the positions of the tongue. However, since it has been shown that vowel /e/ can be produced by deliberately pushing out the tongue, in the present study a vowel triangle structure was made with three vowels: a front-high vowel /i/, a back-low vowel /a/ and a back-high vowel /u/. To examine the intelligibility of the vowels, the CSL (Computerized Speech Lab, Model 4508) program of Kay Co. was utilized to analyse the vowels' formants. Each vowel has multiple formants that reflect the horizontal and vertical positions of the tongue and the shapes of the lips when the vowel is produced. Therefore, it is considered that if these formants have frequency bands different from those of normal hearing children, the articulation producing patterns of hearing-impaired children can be figured out and designing articulatory treatment will become easier. In addition, since sufficient auditory compensation will be provided if hearing-impaired children receive cochlear implants, changes in articulatory abilities can be examined in relation to age at cochlear implantation.

To collect voice samples, the study subjects first went into the voice test room one by one to hear explanations about the purpose and process of the test. At this time, to relieve tensions about or objections to the test, the subject's psychological stability was induced through multiple practice vocalizations. The practice vocalizations were performed 2-3 times and then samples were collected through a microphone at a certain distance while natural voice volumes and vocalizations were maintained. When stable voices were produced, the subjects were induced to vocalize the target vowels /a/, /i/ and /u/ and all the voice samples of individual vowels vocalized by the children were individually stored as wav files. To analyse the voice samples, the voice samples were captured at a sampling rate of 22000Hz and, from each of the samples, 5msec sections at the beginning and ending of the vocalization were removed to analyse sections where long comfortable and stable voices were produced if possible. From the sample voices, F1 (first formant) and F2 (second formant) were examined to analyse the relationship between F1 and F2 in an attempt to figure out speech intelligibility and articulation producing patterns.

3. Data Analysis

Kruskal-Wallis test was conducted to compare the voice data of the experimental group and the control group with each other and Mann-Whitney test was conducted as ex-post analyses. The acoustic characteristics of individual groups were presented in triangle models to compare the movements of articulators for the first and second formants with each other.

Ⅲ. Results

This present study was intended to examine the phonetic features of the vowels of hearing-impaired children in relation to their age at cochlear implantation in comparison with the phonetic features of the vowels of normal hearing children who use Korean.

1. Normal hearing

The results of analysis of the phonetic features of the vowels produced by normal hearing children are as shown in Table 2.

Table 2. F1 & F2 of vowels for hearing-impaired children (Hz)

	/a/		/i/		/u/	
	Mean	*SD*	*Mean*	*SD*	*Mean*	*SD*
F1	1053.70	62.09	400.52	41.10	445.22	52.99
F2	1456.55	132.12	3308.9	354.27	997.76	133.53

On reviewing the vowel formants of normal hearing children, it can be seen that in the case of vowel /a/, the frequency bands of F1 and F2 are very close to each other compared to vowel /i/ and that in the case of vowel /i/, the frequency bands of the two formants are farthest from each other among the three vowels. In addition, in the case of vowel /u/, the two formants form a little low frequency bands. These results are identical to the frequency bands of the formants of normal hearing children.

2. Hearing-impaired children who received cochlear implants before they became 6 years old

The results of analysis of the phonetic features of the vowels produced by hearing-impaired children who received cochlear implants before 6 years of age are as shown in Table 3.

Table 3. The F1 & F2 (Hz) of each vowel produced by hearing-impaired children who received cochlear implants before they reached 6 years of age

	/a/		/i/		/u/	
	Mean	*SD*	*Mean*	*SD*	*Mean*	*SD*
F1	1110.936	79.77	435.016	25.85	588.654	116.06
F2	1614.81	191.74	3382.772	181.94	1188.972	112.86

The results of an examination of the vowel intelligibility of hearing-impaired children who received cochlear implants before 6 years of age showed formants with similar frequency bands to those of normal hearing children. Distances between the formants also showed shapes shown by typical hearing children. Based on these results, it can be seen that if hearing-impaired children who received CIs before they reach the age of 6 years wear cochlear implants for a long time, their vowels will become clear like those of hearing children.

3. Hearing-impaired children who received cochlear implants after they reached 6 years of age

The results of analysis of the phonetic features of the vowels produced by hearing-impaired children who received cochlear implants after 6 years of age are as shown in Table 4.

Table 4. The F1 & F2 (Hz) of each vowel produced by hearing-impaired children who received cochlear implants after they reached 6 years of age

	/a/		/i/		/u/	
	Mean	*SD*	*Mean*	*SD*	*Mean*	*SD*
F1	1294.036	219.97	573.25	159.99	604.914	241.38
F2	2906.584	636.31	3081.796	517.02	1573.04	544.37

The results of examination of the vowel intelligibility of hearing-impaired children who received cochlear implants after they reached 6 years of age showed formants with higher frequency bands to those of normal hearing children. Distances between the formants also showed some differences from those of normal hearing children. That is, it can be seen that in the case of vowel /a/, the distances increased compared to normal hearing children, while in the case of vowel /i/, the distances decreased a little as the frequency of F1 became higher. Based on these results, it can be seen that the horizontal and vertical movements of the tongues of these children are a little different from those of normal hearing children.

4. Comparison of phonetic features among the three groups

The differences in vowels among hearing-impaired children who received cochlear implants before and after 6 years of age and normal hearing children are reviewed as shown in Table 5.

Table 5. Comparison of F1 & F2 of vowels /a/, /i/ and /u/ among 3 groups

		Mean difference	*U*
F1 in /a/	NH -CI before 6 years old	-57.23	.79
	NH - CI after 6 years old	-240.33^{*}	.046
	CI before 6 years old-CI after 6 years old	-183.10	.138
F1 in /i/	NH - CI before 6 years old	-34.49	.841
	NH -CI after 6 years old	-172.73^{*}	.038
	CI before 6 years old-CI after 6 years old	-138.23	.10
F1 in /u/	NH -CI before 6 years old	-143.43	.353
	NH - CI after 6 years old	-159.69	.282
	CI before 6 years old-CI after 6 years old	-16.26	.985
F2 in /a/	NH -CI before 6 years old	-158.26	.802
	NH - CI after 6 years old	-1450.04^{**}	.000
	CI before 6 years old-CI after 6 years old	-1291.774^{**}	.001
F2 in /i/	NH -CI before 6 years old	-73.87	.949
	NH - CI after 6 years old	227.104	.619
	CI before 6 years old-CI after 6 years old	300.98	.441
F2 in /u/	NH -CI before 6 years old	-191.196	.641
	NH - CI after 6 years old	-575.26^{*}	.043
	CI before 6 years old-CI after 6 years old	-384.07	.199

($^{*}p<.05$, $^{**}p<.005$)

As shown in Table III.4, it was shown that, in the case of vowel /a/, the frequency bands of formants exhibited significant differences among the three groups. On the other hand, it was shown that, in the case of vowels / i/ and /u/, the frequency bands of formants exhibited significant differences between the control group and hearing-impaired children who received cochlear implants after they reached 6 years of age.

Vowel triangle models were constructed based on the frequency bands of the formants of vowels of the three groups as shown in Figure 1.

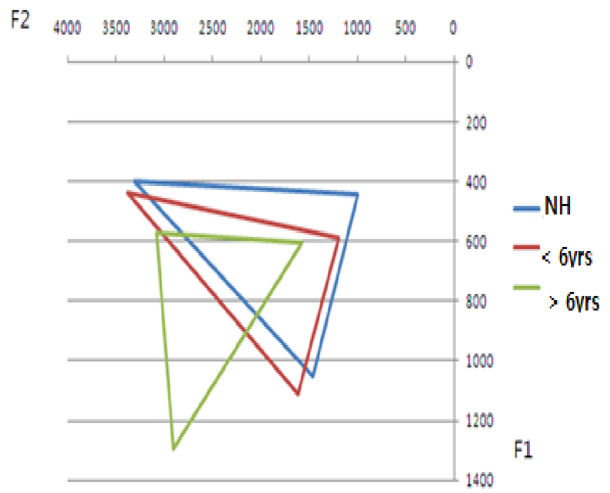

Figure 1. Vowel triangle diagram models of the three groups:

Whereas hearing-impaired children who received cochlear implants before they reached 6 years of age and normal hearing children formed similar vowel triangle models, hearing-impaired children who received cochlear implants after they reached 6 years of age formed a different triangle model. In particular, the products of vowel /a/ showed distorted patterns.

As shown in Figure 1, it can be seen that the vowel triangle diagram constructed by the vowels of normal hearing children and the vowel triangle diagram constructed by the vowels of hearing-impaired children who received cochlear implants before 6 years of age formed quite similar models. By contrast, the vowel triangle diagram of hearing-impaired children who received cochlear implants after they reached 6 years of age was of a completely different shape. In particular, it can be seen that the frequency of vowel /a/ of hearing-impaired children who received cochlear implants after 6 years of age was produced by pushing the tongue forward further compared to hearing-impaired children who received cochlear implants before 6 years of age and normal hearing children.

Ⅳ. Discussion

This present study was intended to examine changes in speech intelligibility, in particular, in the phonetic features of vowels in relation to the age at which hearing-impaired children were implanted with cochlear implants. Differences in vowel intelligibility between hearing impaired children who received cochlear implants before 6 years of age and hearing impaired children who received cochlear implants after 6 years of age were examined and the levels of vowel intelligibility of the hearing-impaired children were examined in comparison with those of normal hearing children. First, the frequency bands of formants of Korean produced by normal hearing children were analysed and based on the results, the frequency bands of F1 and F2 of vowel /a/ were shown to be 1053.7Hz and 1456.5Hz, respectively. Those of vowel /i/ were 400.5Hz and 3308.9Hz, respectively, and those of vowel /u/ were 445.2Hz and 997.8Hz, respectively. It can be seen that these frequency bands are similar to the frequency bands of children reported in a study by Peterson and Barney(Peterson & Barney, 1952). In general, whereas vowels in English are divided into more complicated sounds compared to vowels in Korean, for instance, vowels /i/ and /I/ and /e/ and /æ/ in English are simplified into vowel /i/ and vowel /e/ when they are produced in Korean. In this present study, Korean vowel /i/ was shown to be similar to the English vowel /i/. As such, diverse vowels can be produced depending of the characteristics of individual countries, although it can be seen that three simple Korean vowels are equipped with articulation structures similar to those of three simple English vowels.

Given the aforementioned results, it can be seen that normal hearing children form formants at certain intervals in each vowel when they produce vowels. This is the reason why normal people can perceive the same vowels when they hear voices from diverse persons even though the sounds or fundamental frequencies (F0) are different (Ross et al., 1991).

Due to their loss of auditory feedbacks, hearing-impaired children show articulation production patterns different from those of normal hearing children. To analyse these phonetic features, formants that are resonance frequencies have been analysed and examined(Eberhard et al., 2002). If hearing-impaired children move the articulators minimally when they produce vowels, the frequency bands of the formants are changed and the intelligibility of articulations can be clearly examined by analysing the frequency bands. Based on the results of such examinations, hearing-impaired children who received cochlear implants before 6 years of age formed formants with similar frequency bands to those of the control group, whereas hearing impaired children who received cochlear implants after 6 years of age formed formants of slightly higher frequency bands compared to normal hearing children. When these two groups were compared with the control group, it was shown that the frequency bands of formants of the vowels produced by hearing-impaired children who received cochlear implants before 6 years of age showed patterns more similar to the patterns of normal hearing children than the frequency bands of formants of the vowels produced by hearing-impaired children who received cochlear implants after 6 years of age. In other words, hearing-impaired children who received cochlear implants before 6 years of age were forming frequency bands of formants similar to those of normal hearing children and their intervals between frequency bands of formants were also similar to those of normal hearing children, and thus the intelligibility of their vowels could be perceived to be a little better. On the other hand, in the case of hearing-impaired children who received cochlear implants after 6 years old, the frequency bands of F1 were higher compared to normal hearing children, the frequency bands of F2 were lower compared to normal hearing children and the frequency bands of F2 of vowel /a/ were high, and thus it can be seen that vowel centralization, in which the tongue's articulatory movements are felt to be concentrated on the centre, was occurring. It can be seen that these are identical to the articulatory characteristics of at least severe hearing-impaired children (Boone et al., 2007). That is, in this present study too, it can be seen that hearing-impaired children who received cochlear implants after 6 years of age were pushing their tongue further forward and upward while they were producing vowel /a/ compared to hearing-impaired children who received cochlear implants before 6 years of age, and that for most of their vowels, they were maintaining vowel centralization patterns, in which their tongue was located in the centre of their mouth. It can be seen that hearing-impaired children who received cochlear implants after 6 years of age were maintaining the same articulation patterns as those of severe hearing-impaired children. It is considered that the reason why previous studies reported that their articulatory intelligibility was improved nevertheless was that when these children were wearing hearing aids.

Sim et al. (2016) reported that the age of 3-6 year-old children was a clear legend, at /i, e/ vowels and the other vowels were unchanged. In other words, it is reported that the children are similar to adult vowels by arranging the vowels located in the middle class according to their age. In this study, the hearing impaired children who had undergone surgery before 6 years of age showed a pattern similar to that of normal children, and children with hearing impairment who were operated after 6 years of age still remained inoperable.

Although the gender distribution of the three groups was different, the CI group after 6 years of age was higher than that of the normal children or the CI group before 6 years of age. After 6 years of age, the cochlear implant group showed a reverse phenomenon even though the resonance frequency was low at puberty. This is probably because the auditory compensation can not be done early enough to have a habitual vocal pattern.

Therefore, whereas articulatory guidance is not necessarily required to be included in language educational courses for hearing-impaired children who received cochlear implants before 6 years of age, because they are more likely to show higher articulation intelligibility compared to hearing-impaired children who received cochlear implants after 6 years of age, articulatory guidance should be included in language educational courses for hearing-impaired children who received cochlear implants after 6 years of age.

In conclusion, through this present study, it can be seen that age of cochlear implantation is very important in improving hearing-impaired children's articulatory functions. There have been previous reports indicating that, in general, speech recognition abilities would be improved over the period of wearing cochlear implants because of auditory compensation, and that this would improve articulation intelligibility(Campisi et al., 2005; Huh et al., 2007; Van Dijkhizen et al., 2011). However, in this present study, it can be predicted that if hearing-impaired children receive cochlear implants after they have reached the age of 6 years, their habits of articulating may have become permanent, thereby reducing intelligibility, and they may experience difficulties in maintaining intelligibility. However, it is considered that, if hearing-impaired children receive cochlear implants early, their articulation intelligibility will be improved. Thus, this present study demonstrates that while sufficient auditory compensation and the period of the compensation are important in developing hearing-impaired children's efficient articulatory abilities, the fact that the age at which provision of auditory compensation is associated with linguistic fixation should also be considered.

The limitations of the study based on the results of this study are as follows. The number of participants is very small. This was in order to constitute a cochlear implant for children to produce spontaneous utterances to take full advantage of the audible feedback by wearing a cochlear implant more than three years. Therefore, it is necessary to conduct follow-up studies on these children in order to examine changes in the articulation clarity of children who were later implanted with cochlear implants. We will also look at the changes in the intelligibility of hearing impaired children according to the timing and duration of cochlear implants by increasing the number of populations.

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