Influence of Upper Frequency Boundary on Consonant Perception in Normal Hearing and Cochlear Implant Adults

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Purpose: Although some studies argue that it is worthy for cochlear implant (CI) users to have frequency information above 3,000 Hz for consonant recognition, it is not clear whether CI patients make use of this information, especially in Korean. In this experiment, we tested whether consonant recognition in CI patients depended on the utilization of information from 3,000 to 8,000 Hz. **Methods:** We conducted consonant recognition tests in Korean [3 syllable structures: vowel-consonant-vowel (VCV), consonant-vowel (CV), and vowel-consonant (VC)] pronounced by one male and one female speakers for 3 normal hearing (NH) and 3 CI adults with 9 low-pass filtering frequency conditions. **Results:** Both groups showed decreased correction scores as cut-off frequency getting lower. CI subjects scored twice errors to NH subjects across frequency conditions. The cut-off frequency of 1,500 Hz brought a significant decrease of consonant recognition. Consonants in VCV syllable recognized better than VC and CV syllable in both groups. Fricatives and affricates in the manner of articulation and alveolar and palatal in the place of articulation are the ones that benefit from high frequency coding. Alveolar plosive sounds were most difficult sounds in both groups and this confirms previous studies of consonant recognition in Korean. **Conclusion:** NH and CI groups demonstrated poorer consonant recognition as cut-off frequency decreased with relatively large decrements of CI group. The information above 3,000 Hz conveys little information for consonant recognition in the normal and CI subjects while some CI subjects utilized information up to 6,000 Hz. There were large individual differences, particularly in CI group.

Key Words: Frequency information, Consonant perception, Cochlear implant.

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INTRODUCTION

In speech, consonants have less energy and lie in relatively higher frequency band than vowels. Consonants were more difficult to identify than vowels, irrespective of age or ear, and accuracy in identification (Goodglass, 1973). Besides, loss of audibility of consonants adversely affects speech perception more than that of vowels (Schow & Nerbonne, 2002). Shannon (2002) reviewed speech perception research over 25 years and concluded that quantity and quality of spectral information seemed to be most critical for speech understanding compare to temporal and amplitude cues. Especially patients with sensory neural hearing loss suffered by deteriorated speech recognition ability due to loss of high frequency audibility. Speech recognition predicted by Speech

Intelligibility Index (SII) indicated deterioration by high frequency components. However, it has been revealed that relatively less impact of high frequency amplification on recognition scores in hearing impaired people (Ching et al., 1998; Hogan & Turner, 1998; Murray & Byrne, 1986; Rankovic, 1991; Turner & Brus, 2001). These phenomena were obvious with severe hearing loss patients (Hogan & Turner, 1998; Turner & Cummings, 1999). Started from Vickers et al. (2001), it has been widely accepted that cochlear dead region can cause these phenomena.

In consonants, manner and place of articulation and voicing are important factors for discriminating speech signals. It has been proved that the place of articulation is more difficult than the manner of articulation (Kim et al., 2014; Milchard & Cullington, 2004; Pisoni & Remez, 2005; Turner & Brus, 2001; Tyler &

Moore, 1992; Välimaa et al., 2002). But, voicing, which is one of the main discriminating features of speech sounds, has not as much impact on speech recognition as place and manner. In Korean language, voicing is even not the discrimination features. The place of articulation and phonation types are also the most difficult features in perception of consonants in Korean language (Kim et al., 2014; Lee & Lee, 2000). With these evidences, we can speculate that frequency bands and features of speech affect speech perception, especially consonant discrimination.

Park & Lee (2001) investigated changes in speech intelligibility with frequency cutting with normal hearing (NH) and high-frequency hearing loss patients in Korean language. Information above 3–4 kHz had least impact on speech recognition with 40–50 dB HL input sounds, which is considered important to identification of many speech sounds in English (French & Steinberg, 1947). In Korean, there is no consonant cluster, which means that it could be assumed Korean consonants can have more vowel transition information. On the other hand, it has been proved that vowel-consonant (VC) is more difficult condition for identifying and producing consonants than consonant-vowel (CV) (Abraham, 1989; Hochmann et al., 2011; Owens et al., 1972). On the contrast, Lee & Lee (2000) showed children with hearing impairment recognized consonants in VC better than that in CV. They explained that this is because there are only seven post-vocalic consonants belonging to stops, nasals, and liquid sounds which are relatively easy to hear. Kim et al. (2014) also demonstrated that final consonants were to be discriminated better in frequency limiting conditions in normal listeners.

Since Miller & Nicely (1955) proposed that the number of errors in perceptual confusion patterns represented differences in speech perception mechanism, many researchers investigated which features of speech affect more than others on speech recognition using the confusion type speech recognition test. The confusion type consonant recognition tests can examine every phoneme in target language regardless of the occurring frequency of the phonemes or linguistic difficulty. In Park & Lee (2001)'s study, they used monosyllable identification test for measuring speech recognition scores. They discussed that the speech materials which contain uneven distribution of phonemes could affect the results of the study. Besides, formant transition between consonant and vowel can affect perception of consonants so that to compare perception among consonants it is needed to use same vowel context. Kim et al. (2014) investigated how normal people perceive Korean consonants using confusion test. However, there has been not many studies conducted to examine how well all the consonants are recognized comparing normal and cochlear im-

plant (CI) users.

CI has been verified as highly valid and reliable device for hearing restoration of severe to profound hearing loss. CI devices provide much clearer speech intelligibility than hearing aids and much more high frequency audibility that assumes to help speech perception. However, researches demonstrated that CI subjects were not able to fully utilize the spectral information provided by the number of electrodes used in their implants (Friesen et al., 2001). The listeners with CI could tolerate a large section of missing spectral information in the middle and basal regions, as long as the rest of the spectrum was intact, on the other hand, speech recognition is severely reduced if the missing spectral information is in the critical low-frequency region (Shannon et al., 2002).

This device is used worldwide, and assumed that it is providing sufficient speech information in all used languages. Frequency allocation of CI has an English basis. Korean might have different major frequency bands from other languages, which is lower than other languages such as English, French, or Russian (De Boysson-Bardies et al., 1989; Kim & Lee, 2001) although several studies argued that no differences were found in long term frequency spectrum across languages (Byrne et al., 1994). Furthermore, in terms of Korean speech, it might have more emphasis on mid and low frequency for discriminating speech (Noh & Lee, 2012) and have different frequency function from English (Lee & Kim, 2012). To investigate on this, comparison on consonant recognition between best CI performers and NH adults was performed using the confusion type of consonant recognition test. We recorded consonant recognition test materials and then gradually cut frequency bands using default frequency allocation setting in Nucleus 24 CI system. In normal subjects, we can observe how frequency bands affect on consonant recognition and compare the recognition difference between NH and CI users. So this investigation intended to demonstrate that 1) the change in consonant recognition abilities of NH and CI subjects with band pass filtering according to the frequency table of Nucleus CI system, 2) the comparison of performance in syllable structures and manner and place of articulation, and 3) analysis on consonant recognition errors of the subjects to examine the recognition characteristics of each subject.

MATERIALS AND METHODS

Subjects

The subjects included three NH adults and three CI users who were all females. In the NH group, their average age was 33 years

(34, 38, and 27 years respectively) and in the CI group, their average age was 28 years (28, 29, and 27 years respectively). The selection criterion of NH subjects was pure tone audiometry (PTA) threshold less than 20 dB HL (250 Hz to 6,000 Hz) and average PTA was 8 dB HL (5, 14, and 5 dB respectively). The selection criteria of CI subjects were 1) post-lingual deafness, 2) less than 40 dB HL CI thresholds, 3) more than 1-year CI experience, and 4) more than 85% of open-set sentence test. The average unaided PTA was 91.7 dB HL and average CI threshold was 34.2 dB HL in the CI group. All the CI subjects wore Esprit3G of Cochlear Ltd. using Advanced Combination Encoder strategy and Only the third subject (CI 3) in the CI group was using contralateral hearing aid. This study was confirmed by Seoul National University Institutional Review Board (IRB number 0805-079-245) and all the subjects were agreed to the condition of the study voluntarily. Information about the CI subjects was provided in the Table 1.

Consonant recognition test and frequency modulation

Speech materials included 18 items of VCV test, 18 items of CV test, and 7 items of VC test. They were one- and two-syllable non-sense syllables composed of VCV, CV, and VC combination with vowel /a/ (Figure 1, 2).

Those were recorded in double-walled sound-proof room by one male and one female talker who used standard Korean language. The speech signal was digitized at a sampling rate 48 kHz with 16-bit resolution. The cutoff frequencies were set according to the default frequency bands setting for Esprit3G. It consisted of nine frequency bands which increase at an exponential rate. And its upper frequency limits were 760, 1,414, 1,080, 1,866, 2,463, 3,347, 4,595, 6,308, and 8,658 Hz. So the experimental band-pass frequency bands were 120–8,658, 120–6,308, 120–4,595, 120–3,347, 120–2,463, 120–1,866, 120–1,414, 120–1,080, and 120–760 Hz.

Using Fast Fourier Transform (FFT) algorithm, the original signals which were recorded as wave files were transformed to frequency based data. In These data, outsides of the target frequency band were 0 processed with a computer program using C lan-

guage, which was developed for this study. A rectangular filter was used for the cutting, which has aliasing distortion at the edge of the signal, but preserves more intensity information than the filters with sloping. The data were inversed to the wave files using Inversed FFT (IFFT) algorithm. These manipulated speech stimuli were randomized in terms of stimuli matrix and frequency. Two sets of the stimuli by the two speakers were used for six subjects. Total 774 number of response were obtained by each subject.

Test procedures

Speech stimuli were transmitted via computer compact disk player in an isolated quiet room. For the NH subjects they were to listen to the stimulus lists in the preferred ear mono-aurally through earphone. They were told to speak out the syllables they heard as they touched the target syllables on the stimulus cards. CI subjects were provided the speech stimuli in the implanted ear through input adaptor and cable that were hooked directly into the speech processors. CI subjects used their final map which has been used more than 6 months and has all 20 electrodes on.

To make results constant, the sound level of stimuli was maximal on the volume setting in the computer and 50% of maximal output on the audio-wave program. The loudness level was reported to be comfortable by the subjects.

aga (아가)	ana (아나)	ada (아다)	ara (아라)	ama (아마)
aba (아바)	asa (아사)	ak*a (아까)	atea (아자)	ate ^h a (아차)
ak ^h a (아카)	at ^h a (아타)	ap ^h a (아파)	aha (아하)	at*a (아따)
ap*a (아빠)	as*a (아싸)	ate*a (아자)		

Figure 1. VCV stimuli list of consonant recognition test. VCV: vowel-consonant-vowel.

ka (가)	na (나)	ta (타)	la (라)	ma (마)
pa (파)	sa (사)	an ^ː (안)	tea (자)	te ^h a (차)
k ^h a (카)	t ^h a (타)	p ^h a (파)	ha (하)	ak ^ː (악)
at ^ː (안)	al (알)	am ^ː (암)	ap ^ː (압)	an ^ː (안)
k*a (까)	t*a (따)	p*a (빠)	s*a (싸)	te*a (차)

Figure 2. CV + VC stimuli list of consonant recognition test. CV: consonant-vowel, VC: vowel-consonant.

Table 1. Demographic information of CI subjects

Categories	CI #1	CI #2	CI #3
Age/sex	28/F	29/F	27/F
Hearing threshold in better ear	100 dB HL	100 dB HL	75 dB HL
CI threshold	30 dB HL	35–40 dB HL	30–40 dB HL
HA use on opposite ear	-	-	+
Duration of deafness	15 yrs	10 mon	20 yrs + 1 mon
Causes of deafness	Progressive	Sudden	Progressive + sudden

CI: cochlear implant, HA: hearing aid

Data analysis

The error analysis was performed to compare NH and CI subjects. It was analyzed by error number frequency and percentage. Mann-Whitney test and two-way ANOVA and post-hoc analysis were used. In addition to this, error matrix was analyzed.

RESULTS

This study meant to analyze and compare Korean consonant recognition errors between NH and CI adults according to the amount of frequency information in speech. The analysis was performed in two folds which were a hearing factor and a speech acoustical factor. The Hearing factor was analyzed by total consonant recognition errors and errors according to the frequency bands and the speech acoustic factor was analyzed by syllable structures and phoneme error analysis.

Comparison of total error between NH and CI

Out of the total 774 mean chance, the error percentages were 19.4% in NH group and 43.5% in CI group. There was a significant difference between NH and CI groups ($z = -3.712, p < 0.001$) (Figure 3). CI group (mean = 336.96, SD = 22.304) made errors about twice than normal group (mean = 150.3, SD = 18.512).

NH subjects made no errors in VCV condition when they had all the frequency information from 120–8,658 Hz. However, VC and CV errors occurred in these frequency bands. NH subjects demonstrated less than 15% of error percentage in each frequency band and syllable structure down to 1,866 Hz for VCV test, 2,463 Hz for CV test and for VC test, which were one or two raw error scores (Table 2). Meanwhile CI group showed more than 15% of error numbers from the beginning and the errors were continuously increased along with frequency reduction. Errors of CI subjects were more increased due to subject #3 (Figure 4). She showed marked error numbers from the beginning of frequency reduc-

tion. She was the only bimodal user and this result revealed that she relied less on CI device than the other two subjects.

Frequency bands and syllable structures

Figure 3 showed that consonant recognition errors were increased along with the frequency reduction in all the subjects. In NH group, nine frequency bands brought a significant difference ($F = 37.843, p < 0.001$). Post-hoc analysis revealed that frequency bands down from 1,414 Hz made significant differences with upper frequency bands. And the errors increased significantly in 1,414, 1,080, and 760 Hz of the upper frequency limits. It is similar in CI group that the frequency bands made a significant difference in consonant recognition errors ($F = 5.775, p = 0.001$), but only 1,080 Hz and 760 Hz bands made significant differences. This is because the errors started to occur with all the frequency information. Figure 4 showed how CI subject #3 affected the error rate in CI group.

With the syllable structures, there were significant differences between subject groups (VCV: $F = 4.116, p = 0.003$, CV: $F = 4.396, p = 0.002$, VC: $F = 7.374, p < 0.001$). VCV structure was the easiest condition in three conditions as predicted (NH: 16.0%, CI:

Figure 3. Consonant recognition errors across average conditions by band-pass frequency cutting of NH and CI subjects ($n = 6$, lower frequency limit = 120 Hz). NH: normal hearing, CI: cochlear implant.

Table 2. Recognition errors by syllable structures and talker's gender in NH and CI subjects (%)

Subjects	No. of error	VCV condition	CV condition	VC condition	Male voice	Female voice
S1	116 (14.8)	34 (10.5)	62 (19.1)	20 (15.9)	61 (15.8)	55 (14.2)
S2	142 (18.3)	49 (15.1)	69 (21.3)	24 (19.0)	60 (15.6)	82 (21.2)
S30	194 (25.1)	72 (22.2)	85 (26.2)	37 (29.4)	89 (23.0)	105 (27.1)
Mean	150.3 (19.4)	51.7 (16.0)	72.0 (22.2)	27.0 (21.4)	70.0 (18.1)	80.7 (20.9)
CI1	281 (36.3)	89 (27.5)	146 (45.1)	46 (36.5)	140 (36.2)	141 (36.4)
CI2	256 (33.1)	84 (25.9)	130 (40.1)	42 (33.3)	123 (31.8)	133 (34.4)
Mean CI1 & 2	268.5 (34.7)	86.5 (26.7)	138 (42.6)	44 (19.2)	131.5 (34.0)	137 (35.4)
CI3	474 (61.2)	176 (54.3)	215 (66.4)	82 (65.1)	244 (63.0)	229 (59.2)
Mean	337.0 (43.5)	116.3 (35.9)	163.7 (50.5)	56.7 (45.0)	169.0 (43.7)	167.7 (43.3)

NH: normal hearing, CI: cochlear implant, VCV: vowel-consonant-vowel, CV: consonant-vowel, VC: vowel-consonant

35.9%). Interestingly, even VC condition (NH: 21.4%, CI: 45.0%) showed less error numbers than CV (NH: 22.2%, CI: 50.5%) in both subject groups, errors in VC started from higher frequency band than the CV condition. The error percentage gap between VCV and CV was greater in CI group (Table 2). Only #3 in CI groups made significantly more errors than normal subjects in the VCV and CV condition and she showed significantly more errors than other five subjects in the VC condition (Figure 5).

Error analysis

CI subjects demonstrated more diffused error patterns than NH subjects as predicted. The most frequent errors were found in consonant /t^h/ within VCV and CV conditions and /k^ɰ/ within VC condition in both subject groups. In contrast, the least frequent errors were different between CI and NH groups, which were /tɛ/ in VCV, /m/ in CV, and /ŋ^ɰ/ in VC in NH group and /tɛ/ in VCV, /k^h/ in CV, and /p^ɰ/ in VC in CI group. As expected, aspirated alveolar sound was the most difficult

phoneme whereas nasal and liquid sounds were easier than the other phonemes in both subject groups which place relatively low frequency range. However, NH and CI subjects recognized lax affricate /tɛ/ sound easily and CI subjects recognized aspirated velar sound as the easiest in CV condition, which were not expected.

In error analysis, we left out CI #3 because she made a lot more errors than the other two subjects and confused error patterns. The normal group and CI #1 and #2 showed about the same substitution patterns that were much more recognition errors in the place of articulation than the manner of articulation (Figure 6, 7). In the CV condition, the errors in the manner of articulation increased in CI #1 and #2, but still the place of articulation was more difficult. NH group showed no manner of articulation substitution in the VC condition, meanwhile, CI #1 and #2 still showed the manner of articulation substitution.

DISCUSSIONS

As expected, CI group made twice more errors than NH group across frequency bands. This may due to the fact that the CI group showed more initial errors and continuously increased error numbers than the NH group. Comparing to 8,658 Hz, consonant recognition errors were markedly increased from 1,414 Hz in the NH group and 1,080 Hz in the CI group. High frequency information upper from 2,000 Hz might be redundant for Korean consonant recognition in normal people. However, it was still important to the hearing impaired people with cochlear implants. It seems that the higher frequency information can help some CI recipients to recognize speech.

Errors in recognition occurred from full frequency informa-

Figure 4. Consonant recognition errors across average conditions by band-pass frequency cutting of individual CI subjects ($n = 3$, lower frequency limit = 120 Hz). CI: cochlear implant.

Figure 5. Consonant recognition errors by band-pass frequency cutting and syllable structures of NH and CI subjects ($n = 6$), lower frequency limit = 120 Hz. NH: normal hearing, CI: cochlear implant.

Figure 6. Consonant recognition errors by band-pass frequency cutting and manner of articulation of NH ($n = 3$) and CI subjects ($n = 2$). NH: normal hearing, CI: cochlear implant.

Figure 7. Consonant recognition errors by band-pass frequency cutting and place of articulation of NH ($n = 3$) and CI subjects ($n = 2$). NH: normal hearing, CI: cochlear implant.

tion from 120 Hz to 8,658 Hz might be due to the following several reasons: first, mono-aural input in the test setting could be one of them. Mono-aural speech input could be difficult condition for consonant recognition and even more difficult for the CI subjects. Second, each consonant in each syllable condition and frequency band had only one opportunity to be heard so that mistakes and attention problems were not controlled and reflected in the error scores. Third, the frequency bands were randomized to get more objectivity against the learning effects, but it brought frustration when the much reduction was presented at the earlier period of test session and made the subjects give up to listen more carefully afterward. This phenomenon was predominant in CI #3. This kind of test procedure could be modified as in Milchard & Cullington (2004) to start with the easiest condition and prevent them becoming frustrated from finding the test too difficult. In this study, a random order of word presentations was employed so that would be enough to minimize learning effects.

The VCV condition was the easiest to recognize consonants as expected and the CV condition was more difficult than VC. It is duplicating Lee & Lee (2000), but contradictory to Noh & Lee (2012). According to these results, information that the adjacent vowels might be helpful for consonant recognition, besides it seems that in Korean preceding vowels had better information for recognition than following vowels had. Also, easy recognition of post-vocalic consonants is one of specific features for Korean language (Lee & Lee, 2000). Besides, Korean consonants cannot stand alone without vowels and the VCV condition is more frequent in Korean than English so that Korean could have advantage in consonant recognition over English.

In both groups, $/t^h/$ was the most difficult consonant in Korean. In English, there are consonants like $/f, v, \theta, \delta/$ which place in higher frequency range and have less energy than $/t^h/$ in Korean (Valimaa et al., 2002). $/s/$ and $/t^h/$ are the highest ones among higher frequency consonants in Korean and the subjects in this study definitely showed the greatest difficulty in the high fre-

quency consonant recognition whereas less errors in /s/ than /t^h/, which can be explained that /s/ phoneme has longer duration of sound than that of /t^h/ phoneme. Easy-to-recognize consonants were diverse in both groups. NH and CI group recognized the lax affricate sound /tɕ/ easiest in the VCV condition. And NH group showed the least errors in nasal sounds in CV (/m/) and VC (/ŋ/) whereas CI group made the least errors in plosive sounds in CV (/k^h/) and VC (/p^h/) conditions. Interestingly, in the CV condition, /la/ was the difficult consonant in CI group, which was one of the easy consonants in the NH group. In the overall perspective, the CI group had difficulties in recognition of nasal and liquid sounds which has lower frequency bands and showed the less errors in NH group. It might be explained that plosive sounds have noise burst which is amplified much in CI device so that recognized easily by CI subjects. Another probable explanation of this result is that the Nucleus CI electrodes are typically not inserted deep enough in the apical turn which is really responsible for recognizing nasal and liquid sounds.

In the NH group, the initial consonant confusion started with the place of articulation and with consonants in relatively low frequency location such as /p/, /t/, /t^{*}/, /d/, /n/, /l/, and /m/. And /t^h/ error, which was the most frequent one, started with 3,347 or 2,463 Hz band. With this result, it seems that the error pattern is more in a uniform deficit (Hornsby & Ricketts, 2006), however in the CI group, the error of high frequency consonants as well as hard-to-discriminate consonants started from the 8,658 Hz band. Besides, the total error percentages showed that high frequency consonants were harder than low frequency consonants, which might support frequency-specific effect in speech recognition (Ching et al., 1998; Hogan & Turner, 1998; Turner & Cummings, 1999). This might be because CI subjects had had less experience of high frequency (Hornsby & Ricketts, 2006).

On the other hand, the recognition of consonants seemed to be influenced by other factors. One of them is the linguistic factor that helps or interferes with the speech recognition. Total number of errors revealed that there was a tendency of increasing errors in high frequency consonants. But, /p^h/ and /tɕ/ were recognized quite easily although they are relatively high frequency consonants in NH group. /ap^ha/, /p^h/ and /tɕ/ have meaning as easy vocabulary and /atɕa/ is a frequently used exclamation expression. In contrast, /at^ha/ does not have meaning in Korean. Meaning of the words is helpful for discriminating speech sounds.

The place of articulation was more difficult than the manner of articulation which is consistent to previous researches (Milchard & Cullington, 2004; Pisoni & Remez, 2005; Turner & Brus,

2001; Tyler & Moore, 1992; Valimaa et al., 2002). CI subjects made more errors in the manner of articulation than NH subjects and this was more prominent in CV condition than other conditions.

In Figure 4, errors in CI group markedly increased because of subject #3. The probable reason is that CI #3 has been used contralateral HA from her young age and not ceased to use it when she got CI surgery and the initial mapping period. She might not rely much on the CI for speech recognition. And she showed more frustration on the test than other subjects which might influence on the results.

In this study, the amplitude of stimuli was reduced along frequencies. This could be a compounding factor to the results of this study because amplitude effects are quite important to consonant recognition. Hedrick & Carney (1997) examined that amplitude effects were more influencing than vowel transition information.

In general, information above 3,000 Hz conveys little information for consonant recognition on this task in the NH and CI subjects. However, some CI subjects did utilize information up to 6,000 Hz. Fricatives and affricates in the manner of articulation and alveolar and palatal in the place of articulation are the ones that benefit from high frequency coding. Alveolar plosive sounds were most difficult sounds in both groups and this confirms previous studies of consonant recognition in Korean. High frequency consonant such as /t^h/ was difficult for both groups but easy consonants were different in NH and CI groups.

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