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Determination of filtering parameters for dichotic-listening binaural hearing aids

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One typical auditory characteristic of the hearing-impaired is large and extensive masking. Dichotic listening, defined as listening to complementary filtered speech signals, has been proposed to cope with this problem. We introduce a dichotic listening technique for binaural hearing aids and the relationship between the effect of this technique and the auditory characteristics of hearing-impaired people. The results of listening tests suggest a relationship between the width of the auditory filter and this technique's effect. Moreover, intelligibility test results obtained using low-frequency-boosted sounds suggest that such dichotic listening reduced the upward spread of masking. We are applying this technique to hearing aid systems and have begun evaluating this hearing aid's performance.

1 Introduction

Sensorineural hearing loss is typically characterized by increased hearing thresholds, reduced dynamic range of hearing, degraded temporal resolution, and reduced frequency selectivity. Among them, the reduction of frequency selectivity engenders remarkable disadvantages through large and extensive masking, particularly of the middle and high frequency components by intense low-frequency components: the so-called upward spread of masking. Several researchers have examined the effects of dichotic listening to discover techniques to cope with the upward spread of masking [1–6]. Dichotic listening generally means listening to a different signal in each ear, but in this context, it means listening to complementarily filtered speech sounds in each ear. The speech signal is divided into two complementary parts in terms of frequency spectra to reduce the masking between contiguous frequency bands. Previous studies have suggested that such dichotic listening fundamentally improves speech intelligibility [1, 2, 4–6]. This paper reports three psychoacoustic experiments that examined further details of the effect of dichotic listening. Experiment 1 investigated simple dichotic listening in which speech signals were divided into two bands. Experiment 2 examined whether dichotic listening was effective by reducing the influence of the upward spread of masking. In Experiment 3, the effects of dichotic listening and the relationship between effective dividing frequency and auditory filter bandwidth were investigated using many listeners.

2 Experiment 1 [7]

First, we examined the effects of dichotic listening on speech intelligibility with a simple filtering scheme. Sound stimuli were divided into two frequency bands to reduce consonant masking by the preceding vowel. In addition, the robustness of dichotic listening under noisy environments was also investigated.

2.1 Experimental procedure

The listening test was conducted in a soundproof room. Speech stimuli were presented to listeners through headphones (Sennheiser HDA-200).

The speech stimuli were nonsense vowel-consonant-vowel (VCV) syllables uttered by a native Japanese female. The first vowel in each VCV syllable was /u/, followed by one of 67 CV syllables that covered all Japanese CV combinations. As dichotic patterns, the speech signal was split into two bands by a low-pass filter (LPF) and a high-pass filter (HPF). Considering the formant frequencies of Japanese vowels [8], the boundary frequency was set to 0.8 kHz between the typical F1 and F2 of Japanese /u/ with 1.6 kHz as the F2 average. As a diotic listening condition, all-pass filters (APF) were used instead of LPF and HPF. The dividing patterns are summarized in Table 1. In diotic listening, stimuli with an amplitude of −6 dB (Diotic−6 dB) were also prepared, because in terms of the binaural summation of loudness, loudness in dichotic conditions is estimated to be about 6 dB lower than in diotic conditions under moderate sound levels [9]. Two kind of noises, speech spectral and road traffic noise were added to the speech signal at a signal-to-noise ratio (S/N) of 4 and 0 dB in terms of the A-weighted level (Table 2). The road traffic noise was recorded on a highway and has prominent low frequency components with from which we expected strong upward spread of masking. The level of the speech signals was kept at the listener's most comfortable level (MCL), determined while the speech signal was presented to both ears without noise. The interval between stimuli was set to 3 s. Listeners were four older persons with mild to severe sensorineural hearing loss. The age, hearing threshold levels and most comfortable levels (MCL) for each listener are shown in Table 3. Listeners were asked to write the perceived syllable down as they heard it.

Table 1: Frequency dividing patterns

condition	left channel	right channel	cross over frequency[kHz]
Diotic	APF	APF	-
Diotic−6 dB	APF	APF	-
Dichotic 0.8	LPF	HPF	0.8
Dichotic 1.6	LPF	HPF	1.6

2.2 Results and discussion

Intelligibility scores for Listener A and the averages of all listeners are shown in Figs.1 and 2, respectively. Figure 1 shows that Listener A's intelligibility score with a Dichotic 0.8 pattern is about 15% higher than in the quiet condition, and scores decrease by worsening the S/N. With a Dichotic 1.6 pattern, the scores are generally lower than those with other patterns. The average scores in Fig. 2 show a similar pattern. To analyze in more detail, we examined the results with a two-way repeated-measure ANOVA. In this analysis, the dividing patterns and noise conditions were treated as between-subject variables and the listener was treated as a repeated-measure. Dividing patterns and noise con-

Table 2: Noise condition

condition	a kind of noise	S/N[dB] (L_{Aeq})	S/N[dB] (L_{eq})
quiet	-	-	-
speech 4dB	speech spectral noise	4.0	4.0
speech 0dB	speech spectral noise	0.0	0.0
road 4dB	road traffic noise on highway	4.0	−12.7
road 0dB	road traffic noise on highway	0.0	−16.7

Table 3: Age, hearing threshold and most comfortable levels on intelligibility tess for each listener

Subject	age	MCL [dBA]	Hearing theshold level (L,R) [dB]
Listener A	69	60.0	(31.3,27.5)
Listener B	66	76.0	(47.5,46.3)
Listener C	64	70.0	(38.8,37.5)
Listener D	71	76.5	(55.0,65.0)

ditions were statistically significant ($p < .01$). The following lists are arranged in descending order of their mean values:

Dichotic 0.8 > Diotic > Diotic−6 dB > Dichotic 1.6

A multiple comparison test (paired t-test with Bonferroni correction) showed significant differences between the following conditions:

- Dichotic 0.8 and Diotic−6 dB
- Dichotic 0.8 and Dichotic 1.6
- Diotic and Diotic−6 dB
- Diotic and Dichotic 1.6

These results indicate that simple dichotic presentation with two bands basically improves the intelligibility of hearing-impaired listeners. In noisy conditions, however, the effects seem relatively small, as observed in previous research [5].

3 Experiment 2 [10]

Previous studies suggested that dichotic listening fundamentally improves speech intelligibility for hearing-impaired people. However, why this algorithm is effective has not yet been clarified. In Experiment 2, we examined the changes of intelligibility scores when the amplitude gain of the low-frequency components was increased to investigate the upward spread of masking.

3.1 Experimental procedure

Speech stimuli were 67 nonsense VCV syllables whose preceding vowel was either Japanese /a/ or /u/. In this

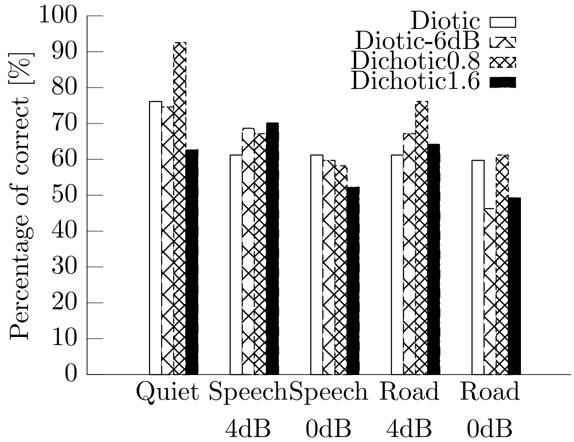


Figure 1: Percentage of correct responses for Listener A

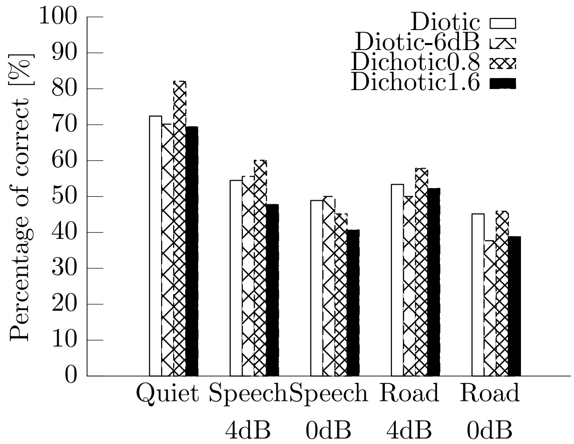


Figure 2: Percentage of correct responses for average of all listeners

experiment, we used the Compensating Loudness by Analyzing Input-signal Digital Hearing Aid(CLAIDHA) algorithm [11] as compensation processing for loudness recruitment. Loudness compensation function (LCF) was decided as follows: in each octave frequency band from 250 to 8000 Hz, we regarded 10 dB as the threshold of normal hearing listeners and 110 dB as the uncomfortable level (UCL). When the level of the input signal was 10 dB, the signal was amplified to the threshold level of each hearing-impaired listener. When the level of the input signal was at 110 dB, the signal was not amplified. The amplitude ratio was linearly interpolated between the level of threshold level of hearing-impaired listeners and UCL. If the level of the input signal was lower than 10 dB, gain was equal to the that of 10 dB-input. In this calculation, the LCF compression ratios of 8.0 kHz were 0.28 (Left) and 0.35 (Right). Since such steepness caused large distortion of the output sound, the compression ratios were set to 0.5 at an LCF of 8000 Hz in each ear.

To make low-frequency-boosted sounds, LCFs of 250 and 500 Hz were modified. In these LCFs, the amplitude gain at an input level of 10 dB was increased 10 and 20 dB from the original gain that was determined by each listener's threshold (CLAIDHA+10, CLAIDHA+20). After these processes, the signal was divided into two complementary parts:

CLAIDHA+10+Dicho and CLAIDHA+20+Dicho.
When /a/+CV speech stimuli were presented, the dividing frequency was set to 1.0 kHz, and when /u/+CV speech stimuli were presented, the dividing frequency was set to 0.8 kHz [12]. The low- and high-frequency components were fed to the left and right channels, respectively. The presentation levels were 40, 50, and 60 dBA. A 71-year-old woman with sensorineural hearing loss (average hearing level 40.0 dB (Left), 32.5 dB (Right)) participated in the experiment. Listener was asked to write the perceived syllables as she heard them. Other experimental conditions were the same as Experiment 1.

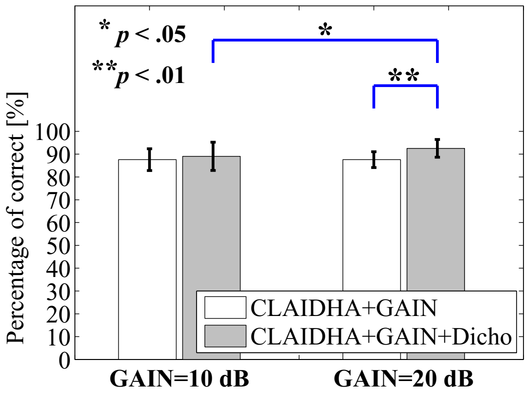


Figure 3: Average of intelligibility scores (/a/+CV syllables)

3.2 Results and discussion

The results of intelligibility tests are shown in Fig. 3. We examined the results using a two-way ANOVA (processing condition (2) and amplitude gain (2)). When /a/+CV syllables were presented, the interaction between the processing condition and the amplitude gain is statistically significant ($F(1,2) = 44.88, p < .05$). Thus the simple main effects were analyzed. As a result, the simple main effect of the processing condition at an amplitude gain of 20 dB is statistically significant ($F(1,4) = 49.39, p < .01$) and that of the amplitude gain under CLAIDHA+GAIN+Dicho conditions is also statistically significant ($F(1,4) = 10.00, p < .05$). Although the intelligibility scores were expected to be higher when the sensation level of the stimulus was larger, there was no statistically significant difference between the intelligibility scores obtained under the CLAIDHA+GAIN conditions. In contrast, certain statistically significant differences were found between the CLAIDHA+10+Dicho and the CLAIDHA+20+Dicho conditions. From these results, the influence of the upward spread of masking, which probably increases when low-frequency-boosted sounds are presented, could be reduced by the using dichotic listening process.

4 Experiment 3

In the above experiments, the number of listeners was very limited. Further investigations with more listeners are required to confirm how the most effective dividing frequency for dichotic presentation depends on listener hearing characteristics. In Experiment 3, we focused on the auditory filter bandwidth as one hearing characteristic.
Two psychoacoustic tests were performed; one is a speech intelligibility test using nonsense VCV syllables, and the other is the measurement of auditory filter bandwidth.

4.1 Speech intelligibility test

4.1.1 Experimental procedure

The listening tests were conducted in a semi-anechoic room. The speech stimuli were nonsense VCV syllables spoken by a native Japanese male and a female. (Note that the VCV syllables by female are the same as the ones in the other experiments of this study). The first vowel in each VCV syllable was one of five Japanese vowels, /a/, /i/, /u/, /e/ and /o/, for the male, and one of two vowels, /a/ and /u/, for the female. The subsequent consonant was one of fifteen Japanese consonants (/#/, /k/, /s/, /t/, /n/, /h/, /m/, /y/, /r/, /w/, /g/, /z/, /d/, /b/, /p/), and the second vowel was /a/. The presentation level of each stimulus was 50 dBA. Before the dichotic listening process, the frequency characteristics of the stimuli were independently adjusted based on the half-gain method at five frequency bands ($fc = 0.25$, 0.5, 1.0, 2.0, and 4.0 kHz) for each listener. In addition, the overall gain of stimuli was subtracted by 3 dB. Note that these processes were performed to simply simulate (a fitting process of) bilateral hearing aids. Four dichotic conditions and a Diotic−6 dB condition were examined in this test. The dividing frequencies of the dichotic conditions were 0.6, 0.9, 1.2 and 1.5 kHz.
The listeners were twelve persons ranging from their 40s to 80s with bilateral sensorineural hearing loss. All usually wore hearing aids in both ears. They were asked to write the perceived syllables as they heard them.

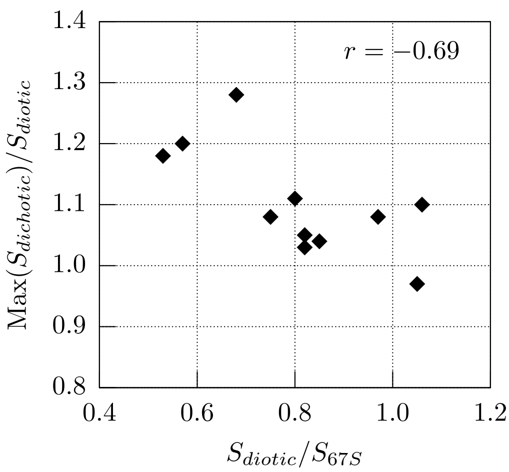


Figure 5: Scatterplot for improvement of intelligibility by dichotic listening($\mathrm{Max}(S_{dichotic})/S_{diotic}$) versus degradation of intelligibility by adding precedence vowel(S_{diotic}/S_{67S})

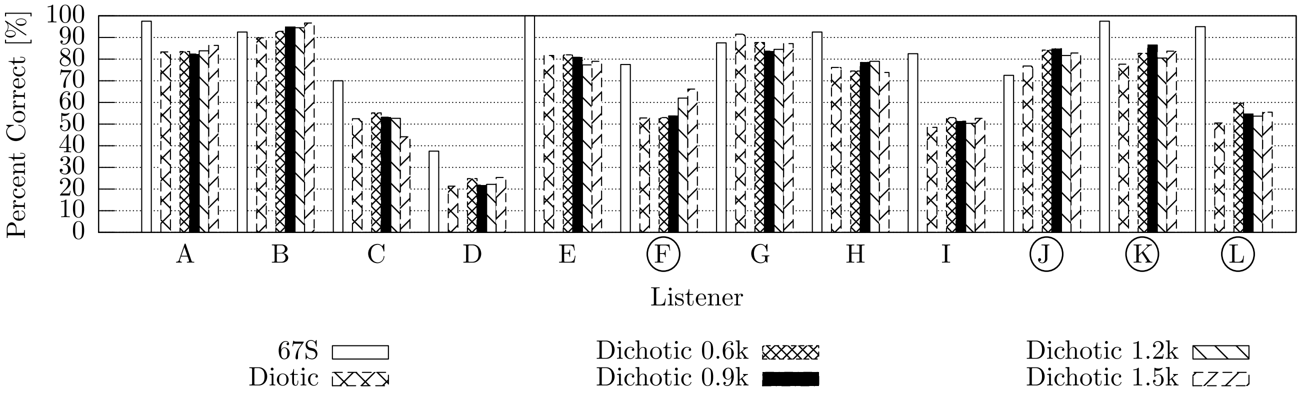
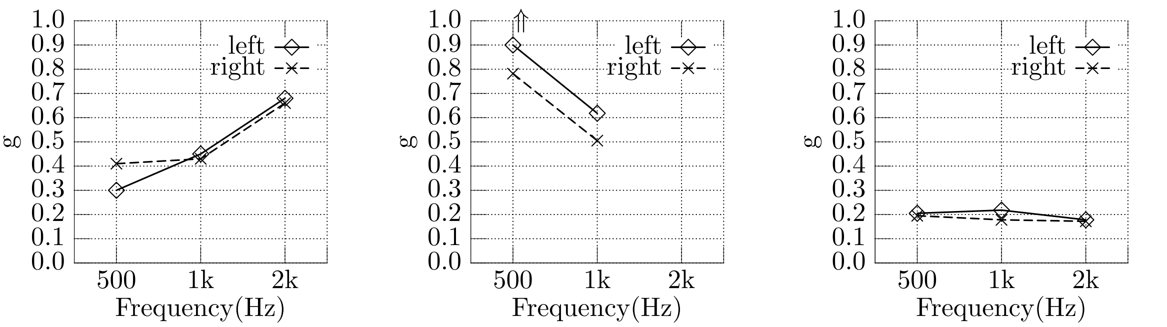


Figure 4: Percentage of correct response for each listener in Experiment 3



(a) Listener F (b) Listener L (c) Listener with normal hearing

Figure 6: Examples of auditory filter bandwidths

4.1.2 Results and discussion

One of the twelve listeners (Listener I), who had difficulty writing down the perceived VCV syllables, was excluded from the analysis of the results. Figure 4 shows the intelligibility scores by VCV syllables for each subject. In addition, the intelligibility scores by the 67-S Japanese monosyllable list, examined prior to this study, are also shown. The 67-S lists, each of which consists of 20 monosyllables each, are widely used in clinics in Japan to assess hearing intelligibilities. For four listeners (F, J, K, and L, indicated by solid circles), the maximum intelligibility scores obtained in the four dichotic conditions are higher than the intelligibility scores obtained in the Diotic−6 dB condition by 8% or more. Moreover, for three of these four listeners (F, K, and L), the intelligibility scores obtained in the Diotic−6 dB condition are lower than those obtained in the 67-S monosyllable test by 20% or more. These results suggest that dichotic listening might be effective for listeners whose intelligibility of VCV syllables is worse than monosyllables, because temporal masking was caused by the preceding vowel. We, therefore, examined the correlation between the degradation of intelligibility by adding the preceding vowel and improving the intelligibility by dichotic listening, as shown in Figure 5. The abscissa is the ratio of intelligibility scores obtained in the 67-S monosyllable tests (S_{67S}) to that obtained in the Diotic−6 dB condition (S_{diotic}), and the ordinate is the ratio of the maximum intelligibility scores obtained in the four dichotic conditions ($\mathrm{Max}(S_{dichotic})$) to S_{diotic}. There is a negative correlation between S_{diotic} / S_{67S} and $\mathrm{Max}(S_{dichotic})$ / S_{diotic} ($r = -0.69$), which means that dichotic listening is more effective for listeners whose intelligibility of VCV syllables is much worse than monosyllables.

4.2 Auditory filter bandwidth measurement

4.2.1 Experimental procedure

The measurement of auditory filter bandwidth was performed in accordance with the method by Nakaichi *et al.* [13]

Probe signals were pure tones of 500, 1000, and 2000 Hz. The signal duration was 500 ms, including 50 ms onset and offset ramps. The signal was repeated, followed by an interval of 400 ms, during each measurement.

The maskers were notched noises, generated by passing a white noise through band-stop filters shaped by 8192-tap FIR filters. The upper and lower cutoff frequencies were symmetrical about the signal on a linear frequency scale; cutoff frequencies were 950 and 1050 Hz when the probe signal was a 1000 Hz pure tone and the bandwidth was 100 Hz.

Auditory filter bandwidth measurements were performed after speech intelligibility tests for each listener. Measurement outlines were as follows:

1. Measurement of probe threshold. The just-audible level of the probe signal was measured three times, using the ascending method of the limits, and the averaged level is defined as probe threshold T [dB SPL].

2. Determination of masker level. The probe level is set to $T + x$ [dB SPL], and a masker (without a notch) is added, whose level is increased gradually in steps of 2 dB. The sound pressure levels of the masker are measured three times, where the listener cannot detect the probe signal. The averaged level is defined as masker level L [dB SPL].

3. Measurement of notch bandwidth. Probe and masker levels are set to $T+x-a$ and L [dB SPL], respectively. The notch bandwidth is increased gradually by steps of $g(= \Delta f/(2fc)) = 0.01$. Value g is recorded three times, where the listener can detect the probe signal again, and then averaged.

In this study x and a were set to 20 and 10 [dB SPL], respectively.
The listeners were the same as in Section 4.1.

4.2.2 Results and discussion

Figure 6 shows examples of auditory filter bandwidths, measured for Listeners F and L, Panels (a) and (b), respectively. For comparison, auditory filter bandwidths measured for a normal listener are shown in Panel (c). The up arrow indicates that value g exceeds 0.9; the auditory filter cannot be measured with this study's experimental scheme. The auditory filter bandwidths of Listeners F and L are extremely wide on higher (2000 Hz) and lower (500 Hz) center frequencies, respectively, compared with a normal listener. Referring to Figure 4, intelligibility scores improved when the dividing frequencies of dichotic listening are high (1200 and 1500 Hz) and low (600 Hz) for Listeners F and J, respectively. These results suggest that dichotic listening would be effective when the dividing frequency is set to where the auditory filter bandwidth is wide.

5 Conclusion

Previous studies suggested that dichotic listening fundamentally improves speech intelligibility. This paper reported three psychoacoustic experiments that clarified further details on the effect of dichotic listening. The results indicate the following: (1) Simple dichotic presentation with two bands basically improves the intelligibility of hearing-impaired listeners. In noisy conditions, however, the effect seems relatively small; (2) The influence of the upward spread of masking is reduced with a dichotic listening process; (3) Dichotic listening is more effective for listeners whose intelligibility of VCV syllables is worse than monosyllables; and (4) Dichotic listening seems effective when the dividing frequency is set where the auditory filter bandwidth is wide.

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References

[1] T. C. Rand, "Dichotic Release from Masking for Speech," *J. Acoust. Soc. Am., 53(3)*, 678-680 (1974)

[2] B. Franklin, "The Effect of Combining Low and Highfrequency Passbands on Consonant Recognition in the Hearing Impaired," *J. Speech Hear. Res., 18(4)*, 719-727 (1975)

[3] H. Kaplan, J. M. Pickett, "Effects of Dichotic/Diotic versus Monotic Presentation on Speech Understanding in Noise in Elderly Hearing Impaired Listeners," *Ear and Hearing, 2(5)*, 202-207 (1981)

[4] T. Lunner, S. Arlinger, J. Hellgren, "8-channel Digital Filter Bank for Hearing Aid Use. Preliminary Results in Monaural, Diotic and Dichotic Modes," *Scand. Audiol., Suppl. 38*, 75-81 (1993)

[5] D. S. Chaudhari, P. C. Pandey, "Dichotic Presentation of Speech Signal with Critical Band Filtering for Improving Speech Perception," *ICASSP '98*, 3601-3604 (1998)

[6] T. Kawase, T. Kobayashi, S. Sakamoto, Y. Suzuki, "Possible use of dichotic listening in hearing aid," *Proc. Spring Meet. Acoust. Soc. Jpn.*, 515-516 (2002) (in Japanese)

[7] A. Murase, F. Nakajima, S. Sakamoto, Y. Suzuki, T. Kawase, T. Kobayashi, "Effect and Sound Localization with Dichotic-listening Digital Hearing Aids," *Proc.* 18^{th} *ICA*, 1519-1522(2004)

[8] T. Oyama, S. Imai, T. Wake, *Handbook of sensation and perception* (Revised edition, Seishinshobou, Tokyo, 1994)

[9] B. Sharf, "Dichotic summation of loudness," *J. Acoust. Soc. Am., 45(5)*, 1193-1205 (1969)

[10] A. Sasaki, A. Murase, S.Sakamoto, Y. Suzuki, T. Kawase, T. Kobayashi, "Application of Dichotic Listening to Hearing Aids," *Proc. 2nd International Symp. on Bio-and Nano-Electronics in Sendai*(2006)

[11] F. Asano, Y. Suzuki, T. Sone, T. Hayashi, M. Satake, K. Ohyama, T. Kobayashi, T. Takasaka, "A method of designing and realizing a digital hearing aid that compensates loudness for impaired listeners," *J. Acoust. Soc. Jpn., 47(6)*, 373-379 (1991) (in Japanese)

[12] A. Murase, S. Sakamoto, Y. Suzuki, T. Kawase, T. Kobayashi, "Effects of dividing frequency in filtering for dichotic presentation to reduce masking to a consonant by the preceding vowel," *Accoust. Sci. & Tech., 27(4)*, 245-247(2006)

[13] T. Nakaichi, K. Watanuki, S. Sakamoto, "A study for simple measurement of auditory filter shapes for each hearing impaired person - A preliminary study for normal hearing subjects -," *Trans. Tech. Comm. Psychol. Physiol. Acoust., H-2000-41, Acoust. Soc. Jpn.* (2000) (in Japanese)