1. INTRODUCTION

The purpose of our previous study [1] was to examine the effect on duration judgment of a center frequency having various bandwidths of bandpass noise. Seven paired-comparison tests were conducted using white noise and six bandpass-noise stimuli with center frequencies of 125, 250, 500, 1000, 2000, and 4000 Hz, and their selected bandwidths (80, 80, 160, 320 and 640 Hz, respectively) were presented first in the pair. The second stimulus was the white noise alone. In the paired-comparison test, 21 subjects judged whether or not the white-noise duration was longer than the bandpass-noise duration, under the conditions of a constant sound pressure level (SPL; 80 dB(A)). The rise and fall times of the stimuli were 2.5 ms and 51.25 ms, respectively. The results indicated that the DS of bandpass noise was judged to be a longer sensation than that of the white noise. The DSs of the bandpass-noise stimuli with lower pitches (larger $\tau_1$) were found to be significantly longer than those of the stimuli with a shorter $\tau_1$ ($p < 0.01$). So, the DS is explained here as one of the primary sensations of the sound stimuli. Another experiment was conducted in which two white-noise stimuli were presented in a pair with different values of $\Phi_0$ (SPL) extracted from the ACF; otherwise conditions were the same as the above. The results indicated that the DS of white-noise stimulus with a higher $\Phi_0$ (80 dB(A)) was found to be significantly ($p < 0.05$) longer duration than one with the lower $\Phi_0$ (50 dB(A)).

Keywords: duration sensation, autocorrelation function (ACF)
phenomena. Auditory sensation is defined here as the first psychological phenomena of sensory area of the brain which, can produce motor responses through perceptual process.

In this connection Oxenham [6] reported on a study of auditory-gap detection in which a larger deterioration was observed when two markers of broadband noise occupied different spectral regions but had the same fundamental frequency. In the classical theory of bandpass noise, the loudness of a bandpass noise remains constant as the bandwidth of the noise increases until the noise reaches the “critical band”, after which the loudness increases with further increases of bandwidth [7-10]. Merthayasa et al. found that the loudness of sharply filtered noise (1080 dB/oct.) centered on 1000 Hz within the critical band is not constant [11, 12]. Florentine et al. compared the loudness of 1000 Hz tones with that of broadband noise over a wide range of levels [13]. They found that the amount of temporal integration, defined as the level difference between equally loud stimuli with durations of 5 and 200 ms, varied with the level. Fujii et al. found that the noise of flying aircraft, which is a mixed state between ‘tonal noise’ and ‘un-tonal noise’, can be well represented by the factors extracted from the ACF and the interaural cross-correlation function [14]. Such aircraft noise may be perceived to behave like a bandpass noise at a lower center frequency.

2. METHODS
2.1 Physical situation of Uhara Hall
The well-known Uhara Hall (not soundproof) in Kobe, a conventional concert hall, was used in this study. The hall is finished in wood and contains 650 seats. The volume of the hall is 4870 m³. One loudspeaker as a source was located at the center of the stage, 1.0 m above floor. The subjects were seated around the frontal side of the central position of the hall. The height of 1.1 m above the floor level corresponds to the ear positions. The distance between the source and the center ear positions of the subjects was 12.5 m. All of the physical conditions are shown in Figure 1 (a and b).

2.2 Stimuli measurement
Impulse responses were measured at the listening position within the subject’s seating area (Figure 1). The measured reverberation times [15] are shown as the ‘T_sub’ in the Figure 2. Five bandpass-noise stimuli were simulated with a cut-off slope of 2068 dB/octave using two distal filters (48 and 140 dB/octave) through a series connection. The center frequencies 250, 500, 1000, 2000, and 4000 Hz were determined with the selected bandwidths 80, 80, 160, 320, and 640 Hz, respectively. The SPLs (Φ(0) of the ACF) of all the direct sounds were measured as 80 dB(A) at the center of the subject’s seating positions, except the SPL (50 dB(A)) of one white-noise stimulus presented first in the pair for the last (7th) session. The rise and fall times were defined by the time for a -3 dB drop from the steady level for all stimuli (Figure 3) and were measured at the center of the listening positions.
shown in the Table 1. The factors $\tau_e$, $\tau_1$, and $\phi_1$ of ACF are defined in Figures 4 and 5, respectively, and were measured at the center listening position, as shown in Table 2 (for calculation see Appendix A).

### 2.3 Subjective test

Seven stimuli consisting of two white noises and five bandpass noises were used in the paired-comparison tests conducted over seven sessions. Each session lasted 4 m and there was a 2 m rest period between sessions except for a 10 m rest period between the 4th and 5th sessions. The duration of the stimuli presented first in the pair was 150 ms. White-noise stimuli was presented ten times in durations of 140 to 230 ms at a step size of 10 ms in the pair. Each pair was presented five times randomly. The SPL of all the stimuli were kept constant at 80 dB(A), except for the white-noise stimulus (50 dB(A)) presented first in the last (7th) session. The intra-pair and inter-pair (response time) gaps were 1 and 3 s, respectively. Twenty-one subjects were asked to judge whether or not the duration of the second of a pair of stimuli seemed longer than the first stimulus. The subjects had to respond by marking a “tick mark” (✓) on the answer sheet when the duration of the second stimulus seemed longer than that of the first, otherwise they had to make a “cross-mark” (x).

### 3. RESULTS

The source stimulus was radiated from the loudspeaker on the stage and was measured as impulse responses by two small microphones placed at the two-ear entrances of a subject. The factor ($T_{sub}$) of the left hemisphere specialization [16] were measured and are shown in Figure 2.

The average value of the five responses at each pair for each subject out of 21 was obtained. The cumulative frequencies of the subjective judgments of all the subjects for the seven different stimuli presented first in the pair are shown in Figure 6. The reference physical duration was 150 ms, and the 50% line of subjective judgments in psychometric function is considered to explain the data. The values on the 50% line of the cumulative frequencies of the averaged subjective judgments are found to be 202.9, 197.5, 185.6, 180.6, and 176.9 ms for the bandpass-noise stimuli, whose center frequencies were 250, 500, 1000, 2000, and 4000 Hz respectively, of their selected bandwidths. The percentages of the judged-longer duration than the standard duration (150 ms) are found respectively, 35.3 %, 31.7 %, 23.7 %, 20.4 %, and 17.9 %. The values for the white noises are found to be 173.0 and 166.0 ms respectively, with the SPL of 80 and 50 dB(A). The 50% line of cumulative frequencies of subjective judgment with individual (21 subjects) differences (standard deviation = 17.19) are shown in Figure 7.

### 4. DISCUSSION

Auditory sensation is described here in respect of stimuli duration. In the paired-comparison test, subjects judged the...
duration comparison between two stimuli in the pair. Such of
judged responses were obtained in the psychometric function
which, was perceived on the basis of sensation of stimulus
duration. Maintaining possible experimental control over the
intervening variables the data of subjective judgments are
explained as duration sensation (DS) as a primary
characteristic of auditory stimuli.

The duration sensations (DS) of bandpass-noise stimuli
were found to be different due to the difference of the center
frequencies. It was clearly seen that the DSs became gradually
longer when the center frequencies belonged to a larger $\tau_1$.

The results of analysis of variance (ANOVA) for the judged-
durations are listed in Table 3. The judged durations for each
individual and the average for the durations of the five stimuli
of bandpass noises were found to be significantly longer ($p <
0.01$) than those of the white-noise stimulus, as shown in
Figure 7. The reverberation conditions include shorter
reverberation times under 1.5 s.

This result is similar to those of the previous study [1] on
the DS for the same stimuli of bandpass noises and white
noise without a reverberation condition. Results described the
relation between DS and $\tau_1$ by

$$\Delta_{DS} = \alpha (\log \tau_1) + \beta$$

here, $\alpha = 16$, $\beta = 10$ and $\Delta_{DS}$ = judged-greater duration than
the judged-white noise duration.

The standard deviations of the individual responses for this
study (21 subjects) was found to be 17.19, whereas, for the
previous study (10 subjects) it was 10.55. Figure 8 shows that
the DS of all the stimuli were found to be shorter under a
reverberation condition, except for two stimuli with center
frequencies of 250 and 500 Hz, than the DS without
reverberation. It is important to understand that the DS is
varied not by the effect of $\tau_e$ but by the effect of $\tau_1$. This result
is similar to that of previous study of Ando et al. [1]. In Table
2, the values of $\phi_1$ is found to have almost the same tendency
as that of the previous study.

Results of another experiment show that the white-noise
duration is judged by a longer sensation when presented under
higher $\Phi(0)$ (80 dB(A)) than that of the lower one (50 dB(A)),
compared with the same white-noise durations (80 dB(A)). It
makes it clear that the $\tau_1$, $\tau_e$, $\phi_1$, and $\Phi(0)$ of the ACF are the
function of DS in which, DS can be recognized as the fourth
primary sensation of sound stimuli in the groups of loudness,
pitch, and timbre [3]. So the DS can be expressed by

$$DS = f[\tau_1, \tau_e, \phi_1, \Phi(0)]$$

### Table 2. Calculated (C) and measured values of $\tau_1$ and $\phi_1$ for the five bandpass-noise stimuli with five center frequencies ($f_c$) and their selected bandwidth ($\Delta f$). W and R indicate without reverberation and reverberation conditions of measurement, respectively.

<table>
<thead>
<tr>
<th>Stimuli</th>
<th>$f_c$ (Hz)</th>
<th>$\Delta f$ (Hz)</th>
<th>$\tau_1$ (ms)</th>
<th>$\phi_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>C</td>
<td>W</td>
</tr>
<tr>
<td>250</td>
<td>80</td>
<td></td>
<td>4.00</td>
<td>4.00</td>
</tr>
<tr>
<td>500</td>
<td>80</td>
<td></td>
<td>2.00</td>
<td>2.00</td>
</tr>
<tr>
<td>1000</td>
<td>160</td>
<td></td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>2000</td>
<td>320</td>
<td></td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>4000</td>
<td>640</td>
<td></td>
<td>0.25</td>
<td>0.25</td>
</tr>
</tbody>
</table>

### Fig. 4. Example of determining $\tau_e$ of the bandpass noise stimulus. The $\tau_e$ is defined by the delay time at which the first envelope of the autocorrelation function becomes -10 dB.

Fig. 5. The $\tau_1$ and $\phi_1$ are defined by the delay time and amplitude, respectively, of the first peak of the autocorrelation function.
5. CONCLUSION

The significant results of the study are cited briefly below.

1. The duration sensations (DS) of bandpass-noise stimuli (five center frequencies with selected bandwidth) were judged to be longer than that of a white-noise stimulus with the same sound-pressure level and duration under reverberation conditions.

2. The DS of the bandpass-noise stimuli with lower center frequencies or lower pitch (larger $\tau_1$) was judged to be longer than those stimuli with higher center frequencies or higher pitches (smaller $\tau_1$) under reverberation conditions.

3. The DS of bandpass-noise stimuli of five center frequencies 250, 500, 1000, 2000, and 4000 Hz with selected bandwidth of 80, 80, 160, 320, and 640 Hz, respectively, were found to be a longer sensation for the higher $\Phi(0)$ (SPL) than for the lower one under reverberation conditions.

4. The DS of bandpass-noise stimuli of five center frequencies 250, 500, 1000, 2000, and 4000 Hz with selected bandwidth of 80, 80, 160, 320, and 640 Hz, respectively, were found to exhibit similar tendencies for both the reverberation and without reverberation conditions.

APPENDIX A

The ACF of the bandpass noises after passing through an ideal filter with upper and lower frequencies $f_2$ and $f_1$ is given by [17]

$$\phi(\tau) = \frac{2}{\Delta \omega \sigma} \sin\left(\frac{\Delta \omega \sigma}{2}\right) \cos\left(\frac{\Delta \omega \sigma \tau}{2}\right)$$

where $\Delta \omega = 2\pi(f_2 - f_1)$ and $\Delta \omega = 2\pi(f_2 + f_1)$.

The envelope of the ACF of the bandpass noises is

$$2 / \Delta \omega \sigma \sin(\Delta \omega \sigma / 2), \text{ for } 0 \leq \Delta \omega \sigma \leq \pi$$

and

$$2 / \Delta \omega \sigma, \text{ for } \Delta \omega \sigma > \pi.$$
The calculated values of $\tau_1$ and $\phi_1$ of the ACF of bandpass-noise stimuli are shown in Table 2 as a parameter of the center frequency with their selected bandwidth.

**ACKNOWLEDGMENTS**

The authors would like to thank to the administrators of Uhara Hall in Kobe, Japan for providing the hall and other facilities used in this study. We also extend our thanks to Hiroyuki Sakai and Takuya Hotehama for their special cooperation. To those who participated in this study as helping hands and as experimental subjects we thank for their kind and active participation.

**REFERENCES**


