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DURATION SENSATION WHEN LISTENING TO BANDPASS NOISES

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The duration sensation of bandpass noise was examined while changing the factors (τ_1, ϕ_1 and τ_e) extracted from the autocorrelation function. The white noise and bandpass noises with six center frequencies (125, 250, 500, 1000, 2000 and 4000 Hz) with different bandwidths were used as stimuli. A paired-comparison test comparing the white-noise duration with bandpass-noise duration was conducted under the conditions of constant sound pressure level (SPL; 80 dB(A)) and rise and fall times (1 ms). Results indicate that the duration of bandpass noise is judged to be longer than that of the white noise. The duration sensation of the bandpass stimuli with longer τ_1 is significantly longer than that of the stimuli with shorter τ_1 ($p < 0{\cdot}01$).

1. INTRODUCTION

A theory on the primary sensation of environmental noise—loudness, pitch and timbre—based on the model of auditory–brain system has previously been described [1, 2]. The sensations of environmental noise can be described by factors extracted from the autocorrelation function (ACF) [3]. The present study is on duration judgment as the fourth-primary sensation of environmental noise.

In the previous study [4], the authors investigated the sensation of duration for stimuli consisting of the white noise with different amplitudes and a pure tone. Thus, the attenuation level of the envelope of the ACF of stimuli ϕ_m ($m = 1, 2, \dots$) is changed by the amplitude difference between the white noise and pure tone. It is found that the duration of stimuli with smaller ϕ_m is judged as longer than that of larger ϕ_m. In the same study, the judgment of a longer duration of sensation for the pure tone is found when the frequency is lower when the tone is lower. Except for the study on the auditory gap detection by Oxenham [5], effects of bandpass noise on the sensation of duration have not been studied before. In this study, a larger deterioration was observed when two markers of broadband noise occupied different spectral regions but had the same fundamental frequency.

The loudness of bandpass noise has been investigated in relation to the center frequency and the bandwidth of the stimulus. In the classical theory of bandpass noise, its loudness remains constant as the bandwidth of the noise increases until the noise reaches the "critical band", after which the loudness increases with further increase in bandwidth [6–9]. Merthayasa *et al.* found that the loudness of sharply filtered noise centered on 1000 Hz (1080 dB/octave) within the critical band was not constant [10, 11]. Ando showed that loudness was increased by the increasing values of effective duration (τ_e) of ACF, which is defined by the delay at which the envelope of the normalized ACF becomes -10 dB [3].

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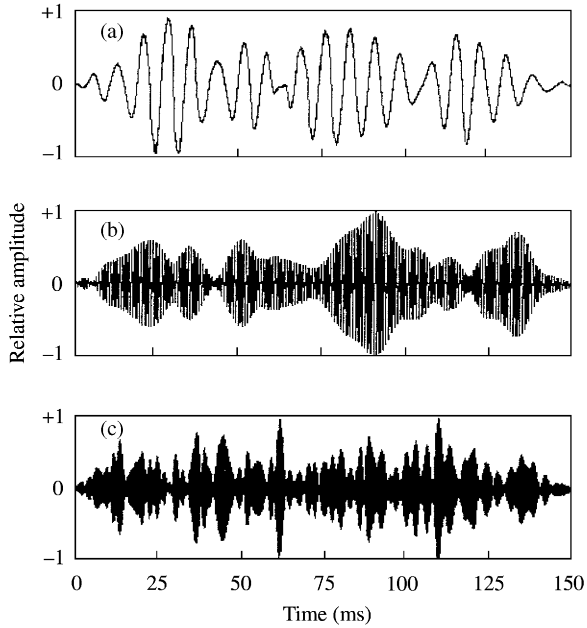

Figure 1. Examples of stimuli used in the study. (a) Center frequency $f_c = 125$ Hz and bandwidth $\Delta f = 80$ Hz; (b) $f_c = 1000$ Hz and $\Delta f = 160$ Hz; and (c) $f_c = 4000$ Hz and $\Delta f = 640$ Hz.

Florentine *et al.* compared the loudness of 1000 Hz tones with that of broadband noise over a wide range of levels [12]. They found that the amount of temporal integration (defined as the level difference between equally louder stimuli with the duration of 5 and 200 ms) varied with level.

Fujii *et al.* found that flying aircraft-noise, which is a mixed state between "tonal noise" and "un-tonal noise", is well represented by the factors extracted from the ACF and the interaural cross-correlation function [13]. Such aircraft noise may be perceived as bandpass noise at the lower center frequency. Examination of effects of the center frequency and the bandwidth of bandpass noises as regards the sensation of duration can be meaningful, if it offers satisfactory explanation by the factors extracted from the ACF. This study investigates the duration sensation of bandpass noises with different center frequencies and bandwidths including critical bandwidth.

2. METHODS

2.1. STIMULI

The white noise and 22 bandpass noises with combinations of six center frequencies (125, 250, 500, 1000, 2000 and 4000 Hz) and different bandwidths were used as stimuli. The stimuli with measured values of τ_1 (●) are shown in Figure 6. The bandwidth was changed with a cut-off slope of 2068 dB/octave, which was obtained by the combination of two digital filters. The bandwidth of 0 Hz means only the slope components. The rise and fall times were defined as the time taken to reach a level -3 dB different from the steady level. The rise and fall times of all stimuli were fixed at 1 ms. Examples of stimuli reproduced by a loudspeaker used in the study are shown in Figure 1.

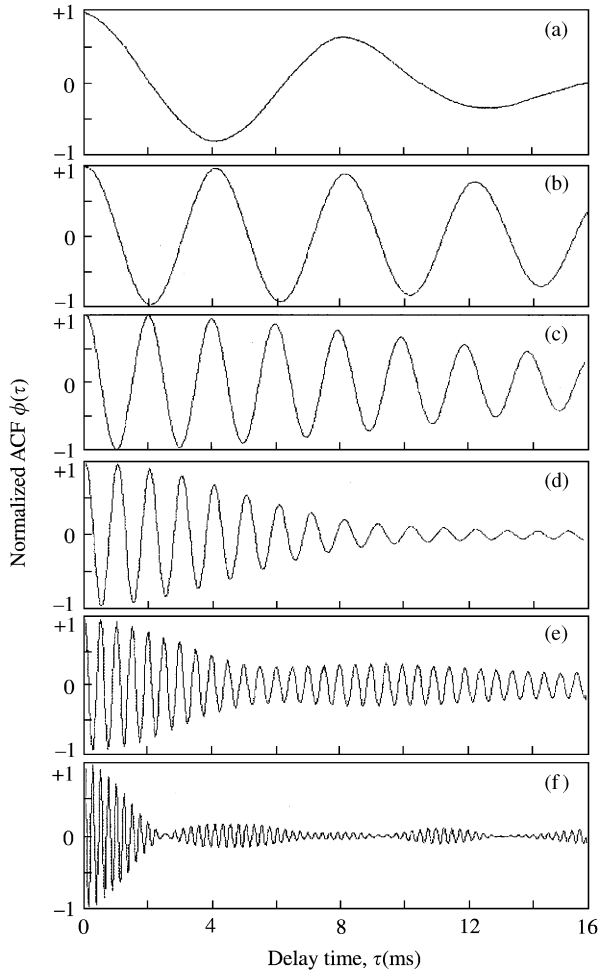

Figure 2. Measured normalized ACF of the six bandpass noises (at the center position of subject's head in the listening room) with different center frequencies (f_c) for selected bandwidths (Δf): (a) $f_c = 125$ Hz and $\Delta f = 80$ Hz; (b) $f_c = 250$ Hz and $\Delta f = 80$ Hz; (c) $f_c = 500$ Hz and $\Delta f = 80$ Hz; (d) $f_c = 1000$ Hz and $\Delta f = 160$ Hz; (e) $f_c = 2000$ Hz and $\Delta f = 320$ Hz; and (f) $f_c = 4000$ Hz and $\Delta f = 640$ Hz.

2.2. ACF MEASUREMENT

Stimuli were characterized in terms of their ACF. All 22 bandpass-noise stimuli were reproduced by a loudspeaker placed inside a soundproof chamber and were recorded by a microphone at a horizontal distance of 74 ± 1 cm from the loudspeaker. The sound pressure level (SPL) of all stimuli was kept constant at 80 dB(A) by measuring the ACF at the origin of the time delay $\Phi(0)$. The normalized ACF of the stimuli after passing through an A-weighted network was calculated [3] (the integration interval of ACF; $2T = 2s$). Examples of the normalized ACF of the six center frequencies at the selected bandwidths are shown in Figure 2. Figure 3 shows examples of the normalized ACF of the six bandwidths centered on 1000 Hz. Definitions of τ_1 and ϕ_1 are the delay time and amplitude, respectively, of the first peak of the ACF as shown in Figure 4. The pitch can be described by τ_1 of the ACF [14]. An example of the determination of τ_e is shown in Figure 5. The value of τ_e represents a repetitive feature or a kind of reverberation contained within the source

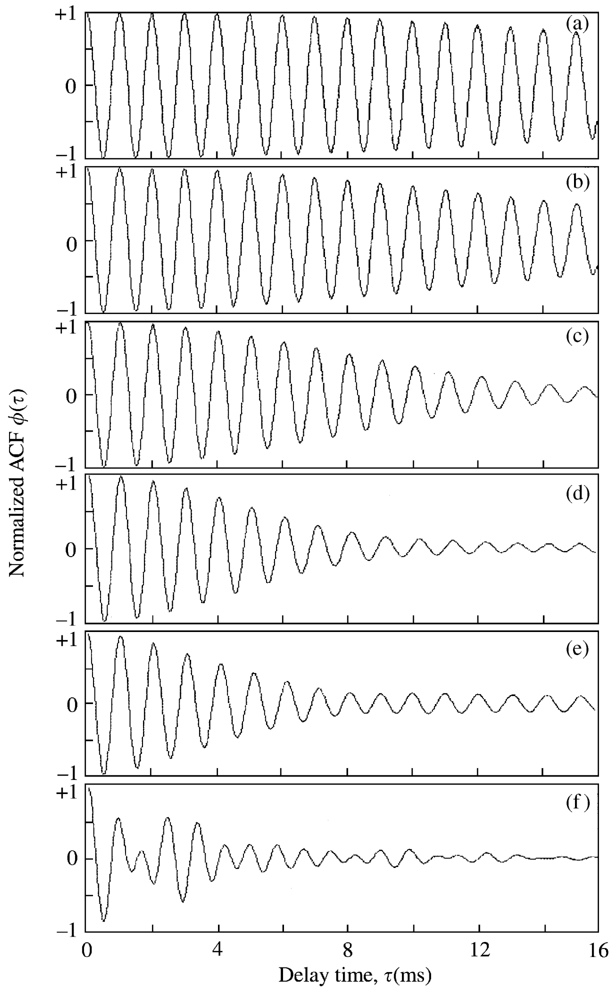

Figure 3. Measured normalized ACF of the six bandpass noises with different bandwidths (Δf) (at the center position of subject's head in the listening room) with a center frequency of 1000 Hz. (a) $\Delta f = 0$ Hz; (b) $\Delta f = 40$ Hz; (c) $\Delta f = 80$ Hz; (d) $\Delta f = 160$ Hz; (e) $\Delta f = 320$ Hz; and (f) $\Delta f = 640$ Hz.

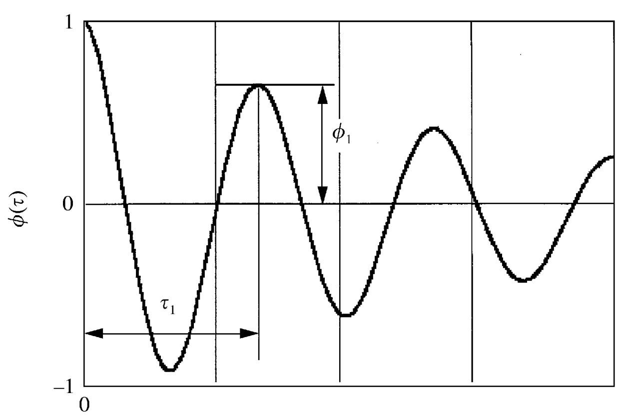

Figure 4. The τ_1 and ϕ_1 are defined by the delay time and amplitude of the first peak of the ACF.

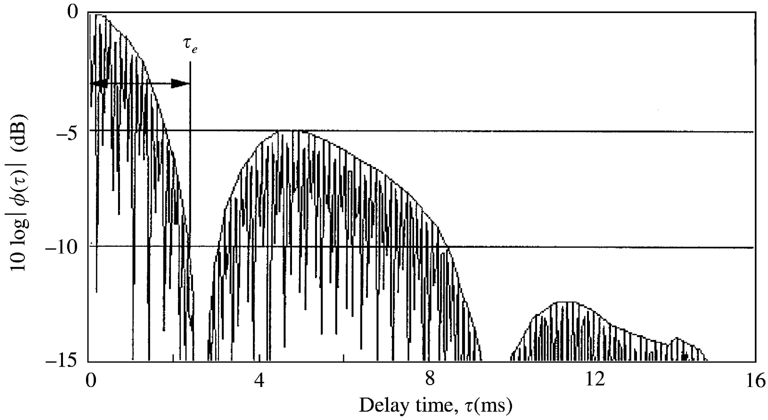

Figure 5. Example of determination of τ_e. The τ_e is defined by the delay time at which the envelope of the ACF becomes − 10 dB.

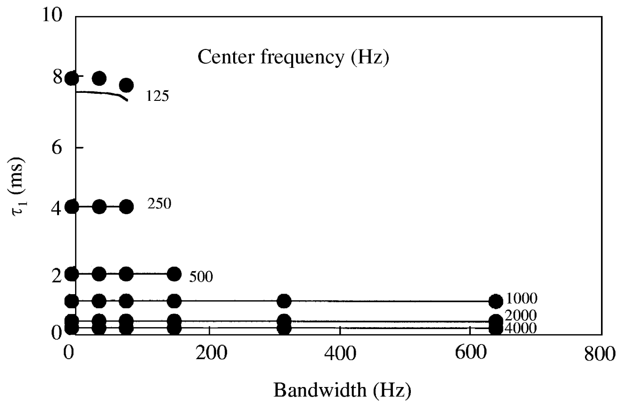

Figure 6. Measured (●) and calculated (——) values (see Appendix A) of τ_1 of the bandpass noises as a function of bandwidth and as a parameter of center frequency.

signal itself. The measured values of τ_1 and τ_e as a function of the bandwidth and as a parameter of center frequency are shown in Figures 6 and 7 respectively. Measured values of τ_1, ϕ_1 and τ_e for the six center frequencies with their selected bandwidths are shown in Table 1. The value of τ_1 corresponded to the center frequency of the stimuli. The value of τ_e increased as the bandwidth decreased and was larger at lower center frequencies.

2.3. SUBJECTIVE JUDGMENT

The duration sensation of bandpass noises was measured by the paired-comparison test. The subject was seated in a soundproof chamber on a chair in front of the loudspeaker. Ten subjects with normal hearing ability participated.

The first stimulus (duration of 150 ms) was a bandpass noise belonging to the combinations of six center frequencies (125, 250, 500, 1000, 2000 and 4000 Hz) and different bandwidths or a white noise in one session. The second stimulus was the white noise. The

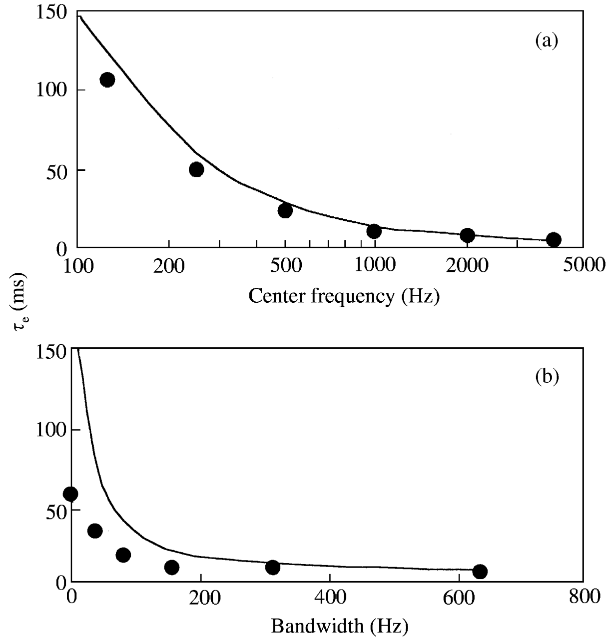

Figure 7. Measured (●) and calculated (——) values (see Appendix A) of τ_e of the bandpass noises as a function of bandwidth. (a) Six different center frequencies with selected bandwidths. (b) Six different bandwidths centered on 1000 Hz.

Table 1

Measured values of τ_1, τ_e and ϕ_1 extracted from the ACF of six bandpass noises for different center frequencies (f_C) with selected bandwidths (Δf)

	τ_1 (ms)	τ_e (ms)	ϕ_1
f_c (Hz) = 125			
Δf (Hz) = 80	7·40	108	0·65
250			
80	4·00	52	0·94
500			
80	2·00	25	0·96
1000			
160	1·00	12	0·97
2000			
320	0·50	8	0·96
4000			
640	0·25	4	0·96

duration of the second stimulus was randomly varied in the range of 140–230 ms in 10-ms steps. Each subject was asked to judge whether the duration of the second of a pair of stimuli was longer or shorter than that of the first stimulus, and to push a particular button only when the second stimulus seemed longer than the first. The intra-pair and inter-pair gaps (for subjective judgments) were 1 and 3 s respectively. Each pair was presented 20 times during each session. Each session lasted about 15 min.

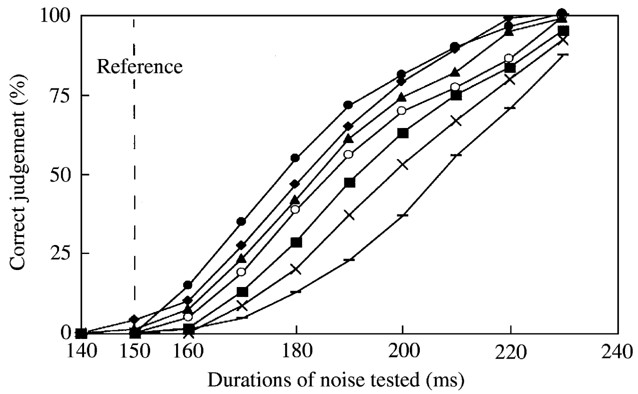

Figure 8. Cumulative frequencies of correct judgments of duration in the paired-comparison test for seven stimuli. The stimuli were six bandpass noises with center frequencies. —, f_c = 125 Hz; ×, f_c = 250 Hz; ■, f_c = 500 Hz; ○, f_c = 1000 Hz; ▲, f_c = 2000 Hz; ◆, f_c = 4000 Hz and ●, white noise. These bandpass noises have selected bandwidths (Δf) of 80, 80, 80, 160, 320 and 640 Hz respectively.

TABLE 2

F-values of the analysis of varience for the judged-durations among the stimuli of white noise and bandpass noises of six center frequencies (f_c) with the selected bandwidths (Δf)

f_c: Δf:	125 80	250 80	500 80	1000 160	2000 320	4000 (Hz) 640 (Hz)	WN
f_c (Hz) = 125 Δf (Hz) = 80	—	3·58	12·38†	24·76†	35·87†	38·77†	68·71†
250 80		—	2·34	8·20†	13·80†	18·00†	34·70†
500 80			—	1·21	3·60	7·34‡	15·20†
1000 160				—	0·69	3·19	9·32†
2000 320					—	1·27	5·42‡
4000 640						—	0·49
WN							—

†idicates 1% significant level.
‡indicates 5% significant level, WN: white noise.

3. RESULTS AND DISCUSSION

Twenty responses of each subject to each-second stimulus duration were obtained. The cumulative frequencies of the correct judgment of duration for the stimuli with the bandwidth of the six center frequencies and the white noise are shown in Figure 8. The durations on the 50% line of the six center frequencies were 208·3 (125 Hz), 199·7 (250 Hz), 192·9 (500 Hz), 188·4 (1000 Hz), 185·5 (2000 Hz), 181·1 (4000 Hz) and 178·5 ms (white noise). The reference physical duration was 150 ms, and the 50% line of correct judgments is defined to be the duration sensation. Results of ANOVA for judged durations are listed in Table 2. The judged-durations for each individual and average for the durations

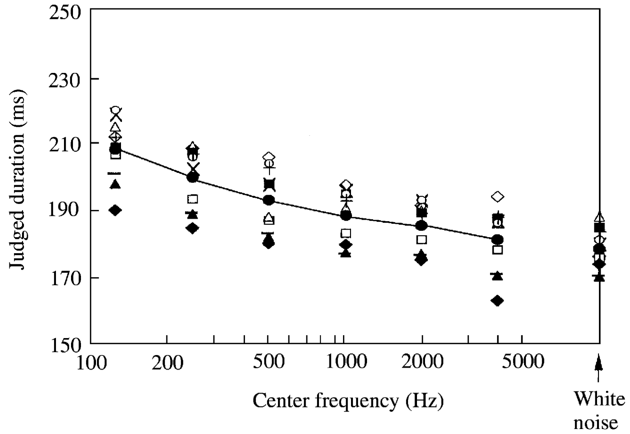

Figure 9. Judged duration of bandpass noises centered on the six different center frequencies with their selected bandwidths and the white noise. The symbols indicate different subjects: ◇, HT; □, YK; △, KT; ×, KK; ■, TH; ○, KS; +, RS; −, SS; ▲, OY; ◆, NK; ●, averaged.

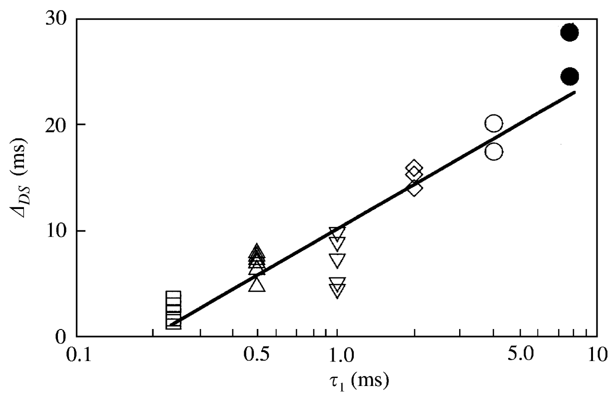

Figure 10. Judged sensation of greater duration (Δ_{DS}) than the white noise as a function of measured τ_1 for 22 stimuli with the combinations of different bandwidths. Symbols indicate different center frequencies: ●, 125; ○, 250; ◇, 500; ▽, 1000; △, 2000 and □, 4000 Hz.

of the six stimuli of bandpass noises were significantly longer ($p < 0.01$) than that of the white-noise stimulus as shown in Figure 9. Standard deviation of the individual data is found to be 10·6 ms.

The longer duration sensation was caused by the longer τ_1 (lower frequencies) of the bandpass-noise stimuli. Thus, the shorter τ_1 or higher center frequency produced a shorter duration sensation (Figure 10). From this figure, the greater-duration sensation judged in reference to the white noise Δ_{DS} may be approximately described by τ_1, so that

$$\Delta_{DS} \approx \alpha(\log \tau_1) + \beta, \tag{1}$$

where $\alpha \approx 15$ and $\beta \approx 10$.

The percentile value ($\Delta_{DS}/150$), for example, at $\Delta_{DS} = 15$ is 10%. This result relating to τ_1 is similar to those in the previous studies on the duration sensation of pure tone [4] and bandpass-noise stimuli [15]. It is worth nothing that DS of complex tones may be described by the value of τ_1 corresponding to the missing fundamental, but not the frequencies of tone [16].

4. CONCLUSIONS

Results of the present study are as follows.

1. The duration sensation (DS) of bandpass-noise stimuli used in this study (combination of six center frequencies and different bandwidths) is longer than that of the white-noise stimulus at the conditions of the same sound pressure level.
2. The DS of bandpass-noise stimuli with lower pitch (longer τ_1) is longer than those stimuli with a higher pitch (shorter τ_1).
3. The values of τ_e and ϕ_1 were found with minor effects on the duration sensation.

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REFERENCES

1. Y. Ando 2001 *Journal of Sound and Vibration* **241**, 3–18. A theory of primary sensations and spatial sensations measuring environmental noise.
2. Y. Ando *Journal of Sound and Vibration* A theory of primary sensations and spatial sensations measuring environmental noise (submitted).
3. Y. Ando 1998 *Architectural Acoustics*: *Blending Sound Sources*, *Sound Fields*, *and Listeners*. New York: AIP Press /Springer-Verlag.
4. K. Saifuddin, H. Sakai and Y. Ando 2001 *Journal of Sound and Vibration* **241**, 117–127. Duration sensation of simulated environmental noise in relation to its autocorrelation function.
5. A. J. Oxenham 2000 *Journal of Acoustical Society of America* **107**, 2215–2223. Influence of spatial and temporal coding on auditory gap detection.
6. E. Zwicker, G. Flottorp and S. S. Stevens 1957 *Journal of Acoustical Society of America* **29**, 548–557. Critical bandwidth in loudness summation.
7. E. Zwicker and H. Fastl 1972 *Journal of Acoustical Society of America* **52**, 699–702. On the development of the critical band.
8. D. D. Greenwood 1961 *Journal of Acoustical Society of America* **33**, 484–502. Auditory masking and the critical band.
9. R. P. Hellman 1970 *Journal of Acoustical Society of America* **48**, 500–504. Effects of noise bandwidth on the loudness of 1000 Hz tone.
10. I Gde N. Merthayasa, H. Hemmi and Y. Ando 1994 *Memoirs of Graduate School of Science and Technology*, *Kobe University* Vol. 12A, 147–156. Loudness of a 1 kHz pure tone and sharply (1080 dB/Oct.) filtered noises centered on its frequency.
11. I Gde N. Merthayasa and Y. Ando 1996 *Proceedings of Japan and Sweden Symposium on Medical Effects of Noise* Vol. 3. Variation in the autocorrelation function of narrow band noises: their effect on loudness judgement.
12. M. Florentine, S. Buus and T. Poulsen 1996 *Journal of Acoustical Society of America* **99**, 1633–1644. Temporal integration of loudness as a function of level.
13. K. Fujii, Y. Soeta and Y. Ando 2001 *Journal of Sound and Vibration* **241**, 69–78. Acoustical properties of aircraft noise measured by temporal and spatial factors.
14. M. Inoue, Y. Ando and T. Taguti 2001 *Journal of Sound and Vibration* **241**, 105–116. The frequency range applicable to pitch identification based upon the autocorrelation function model.
15. K. Saifuddin and Y. Ando 2001 *Journal of Temporal Design in Architecture and the Environment*. Duration sensation when listening to bandpass noises in a room (accepted).

16. K. SAIFUDDIN, T. MATSUSHIMA and Y. ANDO 2001 *Journal of Temporal Design in Architecture and the Environment*. Duration sensation when listening to complex tone and pure tone (submitted).
17. Y. ANDO 1982 *Journal of Acoustical Society of America* **71**, 616–618. Perception of coloration in sound field in relation to the autocorrelation function.

APPENDIX A

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

$$\phi(\tau) = \frac{2}{\Delta\omega\tau} \sin\left(\frac{\Delta\omega\tau}{2}\right) \cos\left(\frac{\Delta\omega_c\tau}{2}\right), \tag{A1}$$

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

The envelope of the ACF of the bandpass noises is

$$2/\Delta\omega\tau \sin(\Delta\omega\tau/2), \quad \text{for } 0 \leqslant \Delta\omega\tau \leqslant \pi$$

and

$$2/\Delta\omega\tau, \quad \text{for } \Delta\omega\tau > \pi. \tag{A2}$$

The calculated values of τ_1 and τ_e as a function of the bandwidth and as a parameter of the center frequency are shown in Figures 6 and 7 respectively. Agreements between them are satisfactory, except for a few cases. Measured values are used throughout this paper.