Duration Sensation When Listening to Bandpass Noises in a Room

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In order to attain knowledge evaluating physical environment in term of the duration sensation (DS) subjective judgments with noise stimuli were conducted here. The DS of bandpass noises in a room was examined while changing the factors (τ_1, ϕ_1, and τ_e) extracted from the autocorrelation function (ACF) under a constant reverberation condition. The white noise and bandpass noises with five center frequencies (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 τ_1) were found to be significantly longer than those of the stimuli with a shorter τ_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)

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 [from Ref. 2] 80, 80, 80, 160, 320, and 640 Hz, respectively. The results of the tests indicated that the white-noise duration was judged to be of a shorter than that of the bandpass-noise duration and a larger τ_1 (τ_1, being the time delay of the first peak of the autocorrelation function) was judged as a longer duration for the bandpass noises. The duration judgment was explained here by the term duration sensation (DS) considering sensation as the root of the subjective judgment [3]. In that study, stimuli were presented by a single loudspeaker in a soundproof chamber without reverberation effects and the subjects were seated alone at the horizontal distance of 74±1 cm from the single loudspeaker. The sound pressure levels as defined by the $\Phi(0)$ in the autocorrelation function (ACF) were kept constant at 80 dB(A). On the basis of those results, another similar study was conducted under a reverberation condition in a conventional concert hall (Uhara Hall) to examine the reverberation effects and the effects of the sound pressure level 'SPL' ($\Phi(0)$) on the DS.

A theory of the primary sensation for environmental noise -loudness, pitch, timbre, and duration- was described by Ando [3]. In this theory, subjective judgments were explained on the basis of its sensation, which is found mutually independent as the four primary characteristics of the neuron. Such a primary sensation of environmental noise can be well described by the factors extracted from the ACF [4]. Saifuddin et al. [5] investigated the duration sensation (DS) for stimuli consisting of white noise having a different amplitude and a pure tone. Thus, the attenuation level of the envelope of the ACF of the stimuli (ϕ_m) was changed by the amplitude difference between the white noise and pure tone. The findings showed that the duration of stimuli with smaller ϕ_m was judged as being longer sensation than that of larger ϕ_m. In the same study, the judgment of a longer-duration of sensation for the pure tone was found when the frequency was lower (larger τ_1) of the tone.

To explain the DS as the primary one this study is designed while the reverberation situation represents environmental 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 m^3. 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,

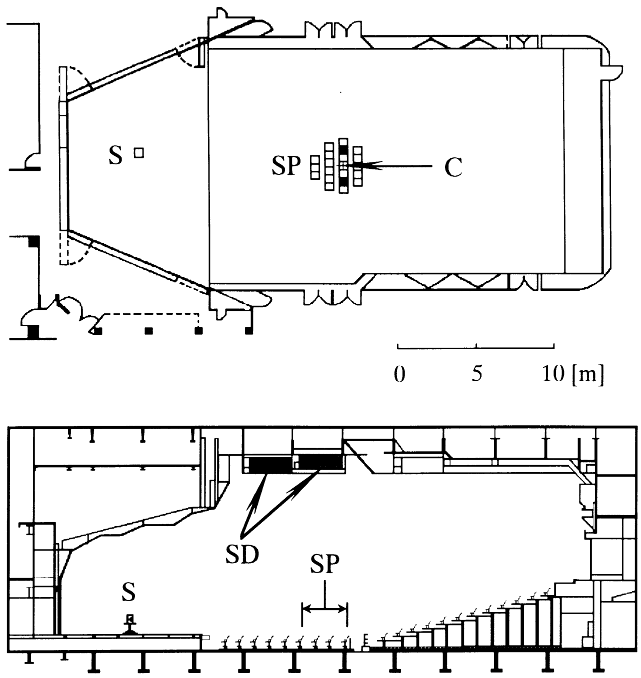

Fig. 1. Seating positions ‘SP’ of the subjects are indicated in plan (a) and cross-section (b) of Uhara Hall, Kobe. Source position ‘C’ indicate where the SPLs were set up and the rise-fall times were measured. Impulse responses were measured at the center hearing position. SD: Schroeder diffuser.

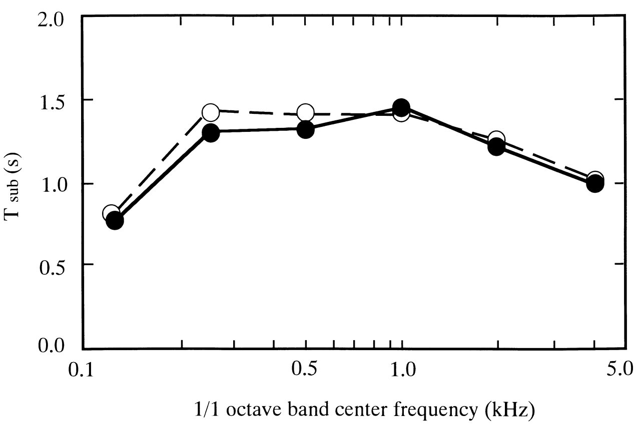

Fig. 2. Values of reverberation time (T_{sub}) obtained from the binaural impulse responses at the center of the subject’s seating area. ‘●’ and ‘○’ indicate the left and right hearing positions, respectively.

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 (7 th) 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 τ_e, τ_1, and ϕ_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.

Table 1. The rise and fall times of the seven stimuli in which five bandpass and two white noises are shown under reverberation condition. The f_c: center frequency and Δf: bandwidth of the bandpass-noise stimuli. WN1 and WN2 indicate white noise with the SPL of 80 dB(A) and 50 dB(A), respectively.

Stimuli		White noise	Rise time (ms)	Fall time (ms)
f_c (Hz)	Δf (Hz)			
250	80		2.3	50.7
500	80		2.4	50.8
1000	160		2.5	51.3
2000	320		2.5	51.5
4000	640		2.6	52.2
		WN1	2.6	51.9
		WN2	2.3	50.8
Average			2.5±0.2	51.3±1.0
Standard deviation			0.14	0.59

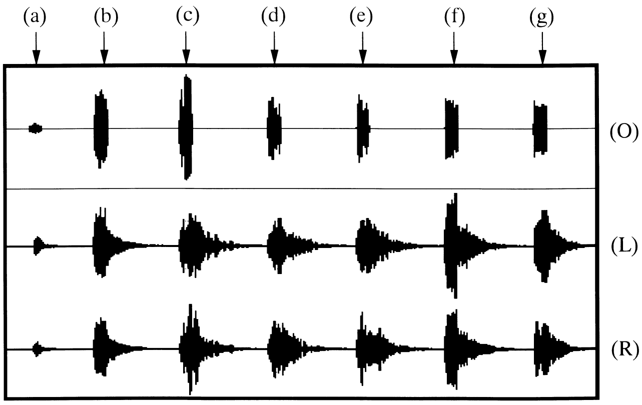

Fig. 3. Examples of stimuli in which 'O' is the original signal without reverberation effects. The stimuli of 'L' and 'R' indicate the left-ear and right-ear hearing position at 'C', respectively with reverberation. (a), (b), (c), (d), (e), (f), and (g) indicate WN 50 dB(A), WN 80 dB(A), BN (f_c: 250; Δf: 80), BN (f_c: 500; Δf: 80), BN (f_c: 1000; Δf: 160), BN (f_c: 2000; Δf: 320), BN (f_c: 4000; Δf: 640). WN: white noise, BN: bandpass noise, f_c: center frequency and Δf: bandwidth. Each stimulus had a constant 150-ms duration.

4. DISCUSSION

Auditory sensation is described here in respect of stimuli duration. In the paired-comparison test, subjects judged the

Table 2. Calculated (C) and measured values of τ_1 and ϕ_1 for the five bandpass-noise stimuli with five center frequencies (f_c) and their selected bandwidth (Δf). W and R indicate without reverberation and reverberation conditions of measurement, respectively.

Stimuli		τ_1 (ms)			ϕ_1		
f_c (Hz)	Δf (Hz)	C	W	R	C	W	R
250	80	4.00	4.00	4.20	0.92	0.94	0.94
500	80	2.00	2.00	2.10	0.95	0.96	0.96
1000	160	1.00	1.00	1.00	0.97	0.97	0.97
2000	320	0.50	0.50	0.50	0.97	0.97	0.97
4000	640	0.25	0.25	0.25	0.97	0.97	0.97

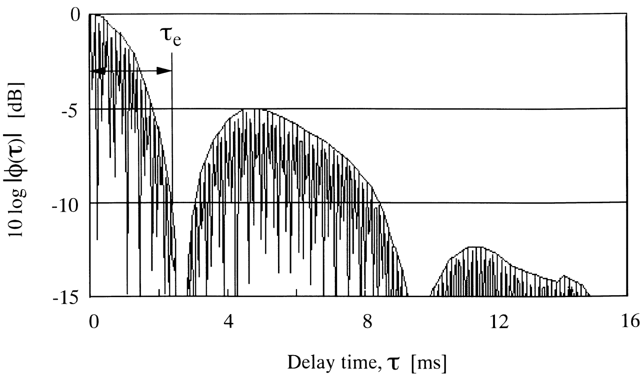

Fig. 4. Example of determining τ_e of the bandpass noise stimulus. The τ_e is defined by the delay time at which the first envelope of the autocorrelation function becomes -10 dB.

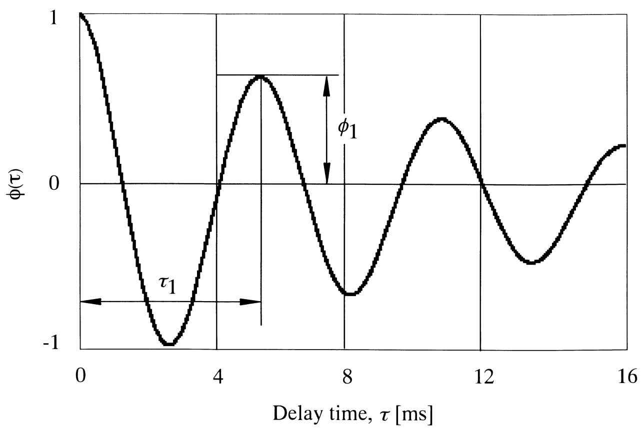

Fig. 5. The τ_1 and ϕ_1 are defined by the delay time and amplitude, respectively, of the first peak of the autocorrelation function.

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 frequency. It was clearly seen that the DSs became gradually longer when the center frequencies belonged to a larger τ_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 τ_1 by

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

here, $\alpha \approx 16$, $\beta \approx 10$ and Δ_{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 τ_e but by the effect of τ_1. This result is similar to that of previous study of Ando et al. [1]. In Table 2, the values of ϕ_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 τ_1, τ_e, ϕ_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

$$DS = f[\tau_1, \tau_e, \phi_1, \Phi(0)] \tag{2}$$

Table 2. F-values of the analysis of variance for the judged durations among the stimuli of white noise (80 and 50 dBA) and bandpass noises of five center frequencies (f_c) with thier selected bendwidths (Δf).

	f_c (Hz) = 250 Δf (Hz) = 80	500 80	1000 160	2000 320	4000 640	WN 80 dB	WN 50 dB
f_c (Hz) = 250 Δf (Hz) = 80		1.77	20.11**	35.38**	49.15**	74.53**	133.11**
500 80		-	7.41**	15.64**	23.63**	37.01**	68.61**
1000 160			-	1.52	4.66*	10.89**	29.91**
2000 320				-	0.88	4.16*	17.60**
4000 640					-	1.11	10.03**
WN 80 dB						-	4.89*
WN 50 dB							-

* and ** indicate 5% and 1% significant level, respectively; WN: white noise.

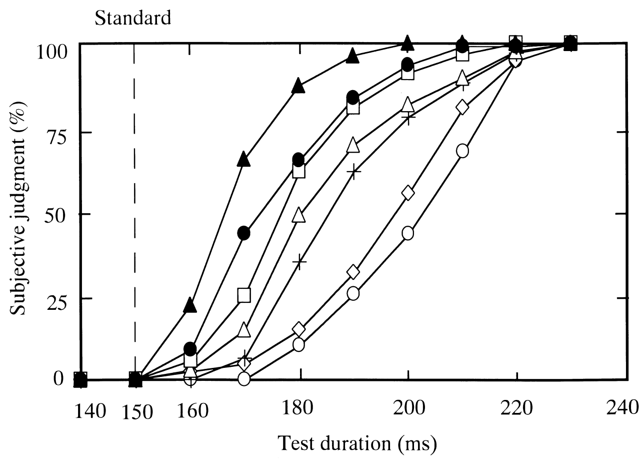

Fig. 6. Cumulative frequencies of subjective judgments of duration in the paired-comparison test for seven stimuli. The stimuli were five bandpass noises with the different center frequencies (f_c) and two white noises with two sound pressure levels. Symbols signify: ○:f_c = 250 Hz; :f_c = 500 Hz; +:f_c = 1000 Hz; :f_c = 2000 Hz; :f_c = 4000 Hz; ●: white noise 80 dB(A); : white noise 50dB(A). The bandpass noises have selected bandwidths (Δf) of 80, 80, 160, 320, 640 Hz, respectively.

here, smaller τ_e and ϕ_1 means minor effect on the DS.

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 τ_1) was judged to be longer than those stimuli with heigher center frequencies or heigher pitches (smaller τ_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 heigher $\Phi(0)$ (SPL) than for of 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 Hx, respectively were found to exhibit similar tendencies for both the revrberation 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]

$$\phi(\tau) = \frac{2}{\Delta\omega\tau}\sin(\frac{\Delta\omega\tau}{2})\cos(\frac{\Delta\omega_c\tau}{2}) \qquad \text{(A1)}$$

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

$$2/\Delta\omega\tau\sin(\Delta\omega\tau/2),\ \text{for } 0 \le \Delta\omega\tau \le \pi \\ \text{and } 2/\Delta\omega\tau,\ \text{for } \Delta\omega\tau > \pi. \qquad \text{(A2)}$$

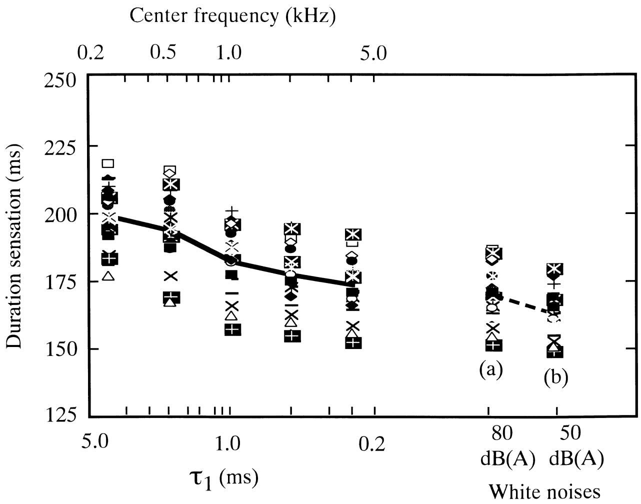

Fig. 7. Judged duration for bandpass noises centered on the five different center frequencies with their selected bandwidths and two white noises. The symbos indicate individual differences of duration sensation by twenty-one subjects (FK, HS, IS, JA, KF, HG, KK, KO, MT, NS, NY, OY, RS, SS, TH, TK, TM, TY, YK, YS, and RM). — : average.

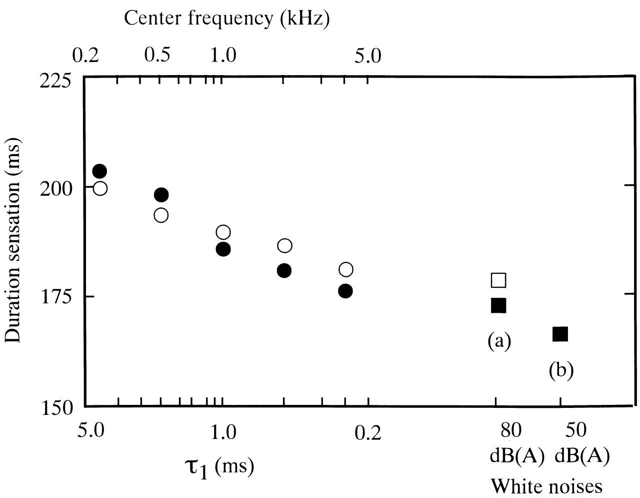

Fig. 8. Duration sensation obtained by cumulative frequencies on the 50% line of subjective judgments in the paired-comparison test for the five bandpass noise and two white noise stumuli. Black circle (●) indicates reverberation condition while white circle (○) indicates without reverberation. (a): white noise 80 dB(A) and (b): white noise 50 dB(A).

The calculated values of τ_1 and ϕ_1 of the ACF of bandpass-noise stimuli are shown in Table 2 as a parameter of the center frequency with their selected bandwidth.

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