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PAPER

Interstimulus interval dependence of the loudness difference limen obtained by taking into account the presentation order effect

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Abstract: This paper describes the interstimulus interval dependence of the loudness difference limen obtained by taking into account the presentation order effect of sound stimuli. A paired comparison experiment of pure-tone sounds was carried out at different interstimulus intervals, and the experimental data were analyzed, taking into account the presentation order effect. The following two characteristic effects were obtained. First, the difference limen changed depending on the interstimulus interval. A logarithmic relation was found between the difference limen and the interstimulus interval. The difference limen was about 0.6 to 1.6 dB at an interval of 0.5 to 64 s. Second, the order effect also changed depending on the interstimulus interval. The sound presented first was perceived as being louder than the sound presented second at an interval of 0.5 to 4 s, and the sound presented second was perceived as being louder than the sound presented first at an interval of 16 to 64 s, although the sounds were of the same sound pressure level. When the interval was 8 s, the sound presented first was perceived as being as loud as the sound presented second. Based on the above findings, we estimated the region where the difference in loudness could not be detected. The obtained results show that the region is not symmetrical for the upper and lower boundary levels.

Keywords: Loudness difference limen, Interstimulus interval, Order effect

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1. BACKGROUND

Subjective evaluation tests of loudness are frequently performed not only in psychoacoustics studies but also in various product development tests. However, if the accuracy of a subjective evaluation test is low, the reliability of the data will be compromised, and the results will be inaccurate. It is, therefore, very important that evaluation tests be carried out accurately. To do that, we must find a suitable method and environment. It is widely recognized that the constant method [1–4], in which sound stimuli are presented randomly and there is a minimal load on the subjects, is one of the most accurate methods. The constant method is used for paired comparisons and it has two important restrictions: do not change any parameters except for the evaluation target, and do not spend a lot of time for the comparison interval to do not forget the first sound. However, changing the target parameters for a very complex or big evaluation target is still a very time-consuming process. In this situation, we need to know how long the subject can retain information about the sound presented in the experiment, and how accurately subjects can detect changes in the sound.

A number of studies on the loudness difference limen have been carried out. For example, Riesz (1928) undertook basic research on the difference limen by using modulation noises [5]. Miller (1947) investigated the difference limen for white noises [6]. Jesteadt (1977) showed the frequency and loudness dependence of the difference limen for pure tones [7]. Clement *et al.* (1999) studied the relationship between the difference limen and the interstimulus interval [8]. However, few evaluated the difference limen taking into account the effect of the presentation order of sound stimuli and the dependence of the limen on the interstimulus interval from a view point of the relationship between sound detection and memory.

2. PURPOSE

The purpose of this study was to obtain the loudness difference limen by taking into account the presentation order effect of sound stimuli (order effect) and to investigate how the difference limen and the order effect vary depending on the interval between the presentation of sound stimuli (interstimulus interval).

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3. EXPERIMENT

We performed a subjective loudness evaluation with two pure-tone signals using a paired comparison experiment.

3.1. Stimulus and Apparatus

We used pure-tone signals at a frequency of 1 kHz as experimental stimuli. The duration of sounds was 3 s with a logarithmic fade-in and fade-out of 0.1 s in order to reduce the transient response. A signal at a sound pressure level of 60 dB was used as the base sound. The sound pressure levels of the comparison sounds ranged from 54 to 66 dB. Around the base-sound pressure level, the sound pressure levels of the comparison sounds were every 1 dB. The SPLs were determined by referring to the previous study on the loudness difference limen [7] in which the difference limen was reported to be about 1 dB. We used nine sound pressure levels—54, 57, 58, 59, 60, 61, 62, 63, and 66 dB—for the comparison sounds. All pairs of the base and comparison sounds were recorded on digital audiotapes and were presented to the subjects binaurally via headphones (Sony closed-type headphones, IDS500). All sound pressure levels were adjusted using a dummy-head microphone (Head Acoustics, HMS-3). This experiment was carried out in a soundproof room (D-30).

3.2. Subjects

Fifteen males, 21 to 24 years old, and five females, 21 to 23 years old, participated in the experiment. All the subjects had normal hearing acuity.

3.3. Procedure

Pairs of a base sound (60 dB SPL) and a comparison sound were presented to each subject using headphones. First, one sound was presented, then the other. The intervals between the two sounds were 0.5, 1, 2, 4, 8, 16, 32, and 64 s. After that, the presentation experiment was carried out for every time interval. The experiment in which the sounds were presented at an interval of 64 s was separated further into two sessions, (i) and (ii), because the experiment was too long. There were, therefore, nine sessions in total. Seven to nine subjects were randomly chosen for each session. Table 1 shows the order of the subjects. Each pair of stimuli was presented three times in random order. There were 189 to 243 trials (9 pairs $\times$ 3 times $\times$ 7 to 9 subjects) for each interval. There were two kinds of trial for each session, one in which the base sound was presented first, and the other in which the base sound was presented second. Each session was between 10 and 25 minutes long. After each presentation, the subjects were asked to respond to the following question on the answer sheet:

Table 1 Order of the subjects.

No.	Name	Sex	Age	Interstimulus interval (s)								
				0.5	1	2	4	8	16	32	64(i)	64(ii)
1	C.A.	M	24							○	○	
2	N.I.	M	23	○	○	○	○		○		○	○
3	Y.K.	M	24					○		○		
4	K.W.	M	24	○		○						
5	T.K.	M	23		○	○	○			○		○
6	E.O.	F	21	○	○		○				○	○
7	R.K.	F	22			○		○			○	○
8	T.S.	F	22	○			○				○	
9	Y.H.	F	21		○					○	○	○
10	Y.S.	F	23					○			○	
11	K.O.	M	22	○		○						
12	S.M.	M	22	○		○		○	○	○	○	○
13	Y.N.	M	23	○			○		○	○		
14	K.N.	M	21	○	○	○			○			
15	K.A.	M	21				○	○				
16	H.T.	M	23		○		○	○	○	○		○
17	M.O.	M	22		○	○	○				○	○
18	K.T.	M	21		○							
19	T.M.	M	21		○	○		○	○			
20	S.Y.	M	24						○			

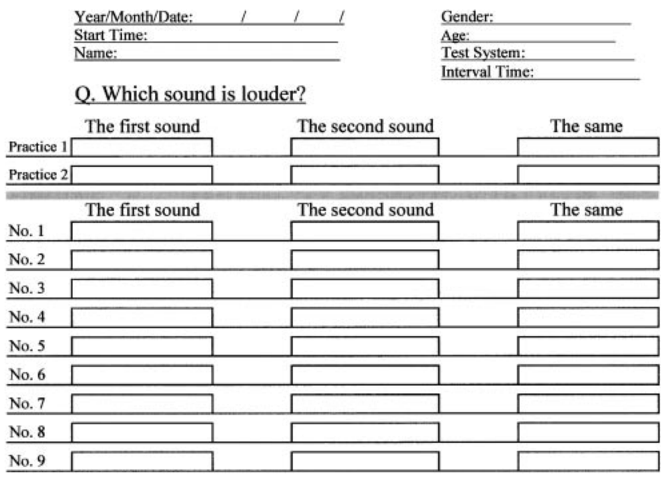

Fig. 1 Answer sheet for the loudness test.

Which sound is louder?

(a) the first sound,
(b) the same,
(c) the second sound.

Figure 1 shows the answer sheet. Each subject had two practice trials before every session.

4. SUBJECT SELECTION FOR ANALYSIS

We performed correlation analyses to remove the outliers (the subjects whose responses were very different from those of the other subjects). Correlation coefficients were calculated for all the subjects and then averaged for each subject. Then the subjects whose averaged correlation

Table 2 Correlation coefficients for the subjects at an interstimulus interval of 8 s.

	Y.K	R.K	Y.S	S.M	K.A	H.T	T.M	Ave.
Y.K	1.00	0.53	0.69	0.81	0.80	0.79	0.84	0.78
R.K	0.53	1.00	0.31	0.07	0.33	0.47	0.49	0.46
Y.S	0.69	0.31	1.00	0.60	0.48	0.54	0.58	0.60
S.M	0.81	0.07	0.60	1.00	0.77	0.74	0.72	0.67
K.A	0.80	0.33	0.48	0.77	1.00	0.84	0.87	0.73
H.T	0.79	0.47	0.54	0.74	0.84	1.00	0.90	0.75
T.M	0.84	0.49	0.58	0.72	0.87	0.90	1.00	0.77
Ave.	0.78	0.46	0.60	0.67	0.73	0.75	0.77	0.68

(Interval = 8 s)

coefficient was under 0.5 were excluded, and the subjects' data were eliminated from the analyses. Table 2 shows the correlation coefficients at an interstimulus interval of 8 s. As a result, one subject was excluded. No subject was excluded at the other interstimulus intervals.

5. ANALYSES

The order effect and the difference limen were calculated by fitting Gaussian distributions onto the response probabilities at the paired comparison at each interstimulus interval [2–4]. To demonstrate the method we used, we use an experimental data set obtained at an interstimulus interval of 1 s. First, we calculated the probability of the subjects' choosing each of the three responses in the answer sheet for the case when the base sound was presented first and for the case when it was presented second. Figure 2 shows the calculated probabilities for the case when the base sound was presented first. When the first sound was 60 dB SPL (the base sound)

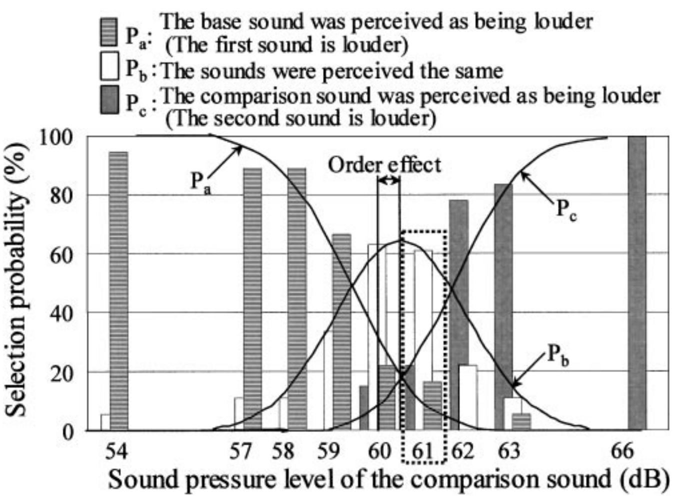

Fig. 2 Selection probability when the base sound was presented before the comparison sound at an interstimulus interval of 1 s.

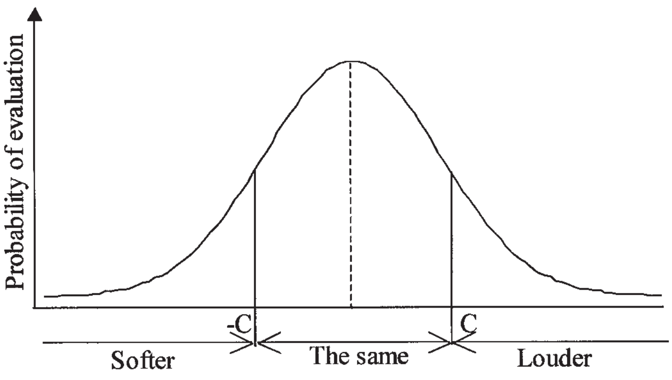

Fig. 3 Probability distribution obtained with three types of response.

and the second sound was 61 dB SPL (a comparison sound), the obtained probabilities P_a, P_b, and P_c were 22, 61, and 17%. This is shown by a dotted line in Fig. 2. Here, P_a, P_b, and P_c indicate the probabilities of the following responses, respectively: "the first sound is louder," "the sounds are the same," and "the second sound is louder."

We assumed that the subjective values of perceived loudness varied according to a Gaussian distribution for the base sound of 60 dB SPL $\phi(x; 60, \sigma^2)$ and for the comparison sound of 61 dB SPL $\phi(x; 61, \sigma^2)$. The distribution of responses in the comparison of these sounds depends on $\phi(x; 61 - 60, 2\sigma^2)$, if these distributions are independent of each other. Figure 3 shows the probability distribution obtained with the three types of response. In this figure, C and $-C$ indicate the cut-off points at which the responses change from "the same" to "louder" and from "softer" to "the same," respectively. When the second sound is perceived as being α dB softer than the first sound depending on the presentation order, the distribution is $\phi(x; (61 - \alpha) - 60, 2\sigma^2)$. By adopting the above assumption, P_a, P_b, and P_c can be represented as follows:

$$P_a = \int_{-\infty}^{-C} \phi(x; (61 - \alpha) - 60, 2\sigma^2)dx,$$

$$P_b = \int_{-C}^{C} \phi(x; (61 - \alpha) - 60, 2\sigma^2)dx,$$

$$P_c = \int_{C}^{\infty} \phi(x; (61 - \alpha) - 60, 2\sigma^2)dx.$$

When the base sound (60 dB SPL) is presented after the comparison sound (61 dB SPL), the distribution depends on $\phi(x; 61 - (60 - \alpha), 2\sigma^2)$. By using this method for all the comparisons at each interstimulus interval, the residual sum of squares (RSS) for all responses between the measured and calculated probabilities from the distribution can be expressed as a function of C, σ, and α. Then, C, σ, and α that give the smallest RSS were calculated, and the most suitable distribution was constructed (Fig. 2). The

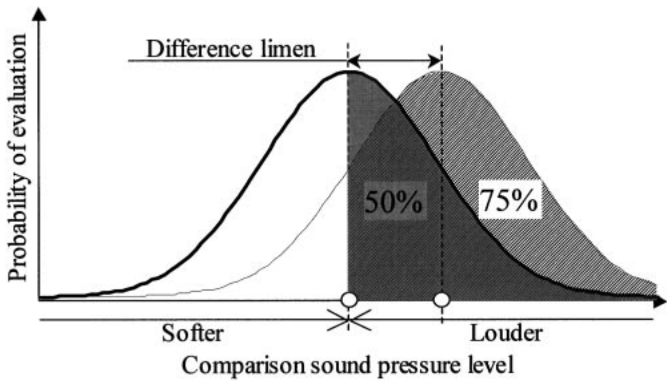

Fig. 4 Probability distribution obtained with two types of response.

thick curves in Fig. 2 show the constructed distributions of P_a, P_b, and P_c. Then α is calculated as the order effect.

To obtain the difference limen, we transformed the Gaussian distribution of the three types of response to the distribution of two types of response. For the transformation, the probability of the "the same" response was equally divided into the probabilities of the "louder" and "softer" responses. Then we can calculate the distribution of two types of response when 50% of responses are "louder." The distribution is shown by the thick line in Fig. 4. We can also calculate the distribution of that when 75% of responses are "louder." The distribution is shown by the thin line in Fig. 4. Thus the difference limen is obtained from the difference of these two distributions. About "softer" response, the same difference limen is obtained in this method.

To investigate how the difference limen and the order effect vary depending on the interstimulus interval, these analyses are carried out at each interstimulus interval.

6. RESULTS

6.1. Loudness Difference Limen

We measured the effect of the interstimulus interval on the loudness difference limen, taking into account the presentation order effect of sounds by using the constant method. The interstimulus interval dependence of the difference limen is shown in Fig. 5. In this figure, the difference limen increases with the interstimulus interval from 0.6 dB at an interval of 0.5 s to 1.6 dB at an interval of 64 s. This tendency was also observed in a previous study [8]. In our study, furthermore, the tendency becomes gentler as the interstimulus interval increases. We derived an approximation function that represents the relationship between the difference limen and the interstimulus interval. The function and its correlation coefficient between the measured and approximated difference limens are shown in Eq. (1):

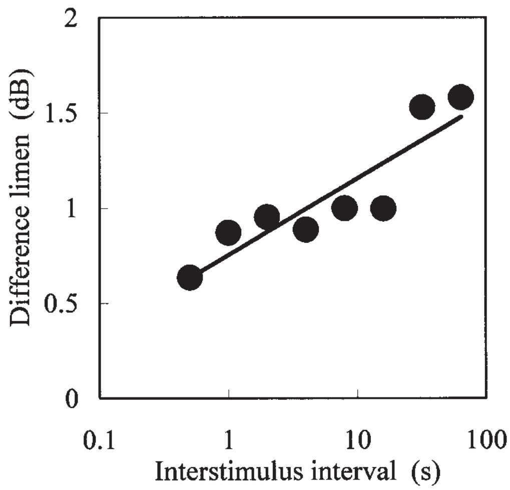

Fig. 5 Interstimulus interval dependence of the difference limen.

$$DL = 0.17 \log IS + 0.75, \quad (1)$$

$$\mathit{Correlation\ Coefficient} = 0.90.$$

where DL is the difference limen (dB), and IS is the interstimulus interval (s). Equation (1) shows that the difference limen could be represented by a logarithmic function of the interstimulus interval.

6.2. Order Effect

Figure 6 shows the relationship between the order effect and the interstimulus interval. This figure shows that at an interval of 0.5 s, the subjects perceived the second sound as being approximately 1 dB softer than the first one, although the sounds were of the same sound pressure level of 60 dB. In contrast, at an interval of 32 s, the subjects perceived the second sound as being approximately 1 dB louder than the first one. When the interval was 8 s, the subjects perceived the first sound to be as loud as the

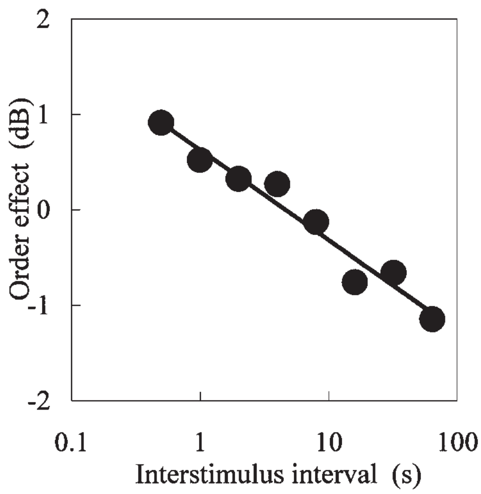

Fig. 6 Relationship between the order effect and the interstimulus interval.

second. The relationship between the order effect and the interstimulus interval is represented by a logarithmic function as well as Eq. (1). Equation (2) shows the function and its correlation coefficient between the measured and approximated order effects:

$$OE = -0.41 \log IS + 0.63, \quad (2)$$

$$Correlation\ Coefficient = 0.98.$$

where OE is the order effect (dB), and IS is the interstimulus interval (s).

6.3. Influence of the Order Effect

We determined the influence of the order effect on the difference limen. To obtain the difference limen without taking into account the order effect, we analyzed the data after combining the responses obtained for both presentation orders.

Figure 7 shows the difference limens obtained by not taking the order effect into account in the analyses (open circles) and by taking it into account (filled circles). This result shows that the difference limen obtained without taking the order effect into account is about 0.5 dB higher than that obtained when the order effect was taken into account.

6.4. Region of Undetectable Difference in Loudness

Using the above results, we estimated the region in which the subjects could not detect the difference in loudness between the base (60 dB SPL) and comparison sounds. Figure 8 shows the region of undetectable difference in loudness when the base sound was presented as the first stimulus. The thick solid line shows the approximated order effect, and the thin solid line shows the difference limen approximated from the results. In Fig. 8, the gray region denotes the region of undetectable difference, where the human ear cannot detect the difference in loudness. As can be seen by a dash-dotted line in Fig. 8, at an interstimulus interval of 32 s, the human ear can detect the difference in loudness between a 60- and a 62-dB SPL signal but not between a 60- and a 58-dB SPL signal, although the SPL difference between the two signals is the same in both cases (2 dB). Three empty points in Fig. 8 indicate the SPLs. This result shows that the region in which the difference in signal loudness cannot be detected is not symmetrical for the upper and lower boundary levels based on 60 dB SPL. When the base sound is presented as a second stimulus, the region of undetectable difference in loudness becomes upside-down to that of the base sound is presented as the first stimulus in Fig. 8.

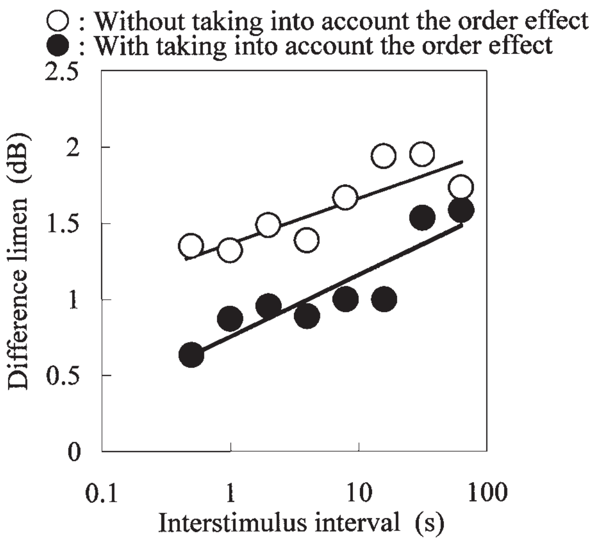

Fig. 7 Difference limens with and without taking into account the order effect.

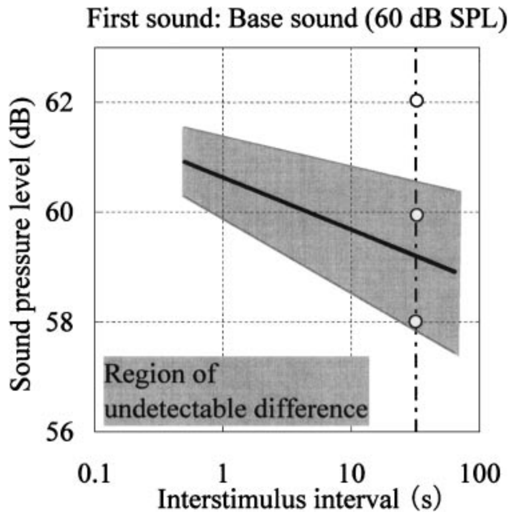

Fig. 8 Region where the difference in loudness cannot be detected.

7. DISCUSSION

7.1. Difference Limen

It is believed that the interstimulus interval dependence of the loudness difference limen is related to the memory system that controls the memory span for auditory information in humans. Atkinson and Shiffrin (1968) carried out a study on the human memory system [9]. They found three types of memory. The first is sensory memory, in which information is held but not processed. Sensory memory for auditory stimuli is called "echoic memory." Humans can hold auditory information in echoic memory for about 5 s. The second is short-term memory. When information is paid attention to, it moves from sensory memory to short-term memory. Humans can retain information in short-term memory for about 15–30 s. The last one is long-term memory. After information has been repeated many times it moves from short-term memory to long-term memory. Humans can retain information in long-term memory indefinitely.

In a recent study, Kaernbach [10] found that information retained in echoic memory was generally forgotten within the first 10 s. It is, therefore, believed that the difference limen is related to echoic memory and is almost proportional to the interstimulus interval of up to 10 s. In our experiment, the subjects retained information about the sound they heard in echoic memory for about 10 s; consequently, the evaluation accuracy was high at the beginning, but it deteriorated rapidly. After the first 10 s, the subjects "moved" the processed sound information into short-term memory, where the evaluation accuracy was lower than in the echoic memory, and it generally deteriorated when the interstimulus interval was up to 30 s. After 30 s, the evaluation accuracy was lower than in the short-term memory because of a long interstimulus interval; however, the evaluation accuracy deteriorated much slower than in the other types of memory.

7.2. Order Effect

It is believed that the interstimulus interval dependence of the order effect is related to auditory adaptation and auditory fatigue. Auditory adaptation is a balance process [11]. When we hear a continuous sound for a long time, after a certain period, we start to perceive the sound as being softer than the sound's original loudness. Auditory fatigue is a temporary threshold shift that occurs just after hearing a loud sound (approximately 120 dB SPL) [11,12]. However, it may occur even at 60 dB SPL [13]. We believe that when the interval was between 0.5 and 4 s, the order effect was affected by auditory adaptation and fatigue. This is why no order effect was observed when the interstimulus interval was 8 s—at this interval the subjects' hearing acuity could recover.

On the other hand, the subjects perceived the first sound as being softer than the second one at an interval above 16 s, although the sounds were of the same sound pressure level of 60 dB. From this result, we believe that the subjects forgot the first sound and the impression of the sound became weaker when the interstimulus interval was long.

8. CONCLUSION

In this study, we investigated the effect of the presentation interval on the difference limen in a subjective loudness evaluation. We carried out a paired comparison experiment with pure-tone signals presented at different interstimulus intervals and analyzed the experimental data taking into account the presentation order effect of the sound stimuli. We obtained the following characteristic effects:

1) The difference limen changed depending on the interstimulus interval, and there was a logarithmic relation between the difference limen and the interstimulus interval. The difference limen ranged from about 0.6 to 1.6 dB at an interstimulus interval of 0.5 to 64 s.
2) The order effect also changed depending on the interstimulus interval and the relationship between the effect and interstimulus interval could be represented by a logarithmic function. The sound presented first was perceived as being louder than the sound presented second at an interval of 0.5 to 4 s, while the sound presented second was perceived as being louder than the sound presented first at an interval of 16 to 64 s, although the sounds were of the same sound pressure level. When the interstimulus interval was 8 s, the first sound was perceived as being as loud as the second one.

We estimated the region in which the difference in loudness could not be detected. The obtained results show that this region is not symmetrical for the upper and lower boundary levels. We believe that these results are useful for subjective evaluation tests of loudness.

In the future, we will investigate the effect of an interval longer than 64 s on subjective evaluation. Additionally, we would like to investigate what kinds of sound are retained in human memory the longest.

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