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Loudness and noisiness of a repeated impact sound: Results of round robin tests in Japan (II)

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This paper reports and discusses the results of the second stage of experiments of a round robin test on the evaluation of impact sounds. Two psychological attributes, loudness and noisiness, were dealt with in this study. The PSE's for both attributes were obtained by using the same experimental procedure. In this study, a repeated impulsive sound whose duration is 3 s at the longest was presented in a diotic listening condition. The results of the study are summarized as follows: 1) The coefficients for linear regressions of PSE on L_{pE} (the frequency-unweighted sound exposure level) were 0.62–0.63 for loudness, while they were 0.93–1.11 for noisiness. This seems to indicate that the time constant for integration of sensation is longer for noisiness than for loudness. 2) For both loudness and noisiness, L_{pE} showed a high correlation with PSE obtained by our experiments, and thus loudness of repeated impulsive sounds might be described by L_{pE} with some modifications, and noisiness can be expressed by L_{pE} with minor modifications. 3) The difference between the results of carrier signals used in this study has little effects on the experimental data.

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1. INTRODUCTION

In evaluating steady or slowly fluctuating noises, L_{Aeq} is widely used today.[1,2] How to evaluate impulsive noise, however, has not yet been made clear.[3] Considering that we often encounter impulsive noise in our daily lives, such as the sound of slamming doors, typewriting, hammering and so forth, the need to establish a method for evaluating such noise is imperative. This paper describes the second set of results of a round robin test carried out in Japan, the purpose of which was to establish a method of evaluating the level of loudness and noisiness of impulsive sounds.

There is a method of evaluating impulsive noise which is being temporarily used. This is the method of using an impulsive adjustment as described in ISO R1996-1971,[4] where 5 dB correction can be added to L_{Aeq} when the noise is impulsive. This value of correction, 5 dB, however, was omitted from ISO/DIS 1996/2-1985.[5]

Regarding instruments for measuring sound, a circuit with an 'I' detector-indicator characteristic of a sound level meter as described in IEC Pub. 651[6] is well known. However, neither the adjustment nor the characteristic 'I' is based on experimental results acceptable to most researchers.

The problem of how to evaluate impact sounds still remains unsolved, though many researchers have studied their loudness and noisiness, and the annoyance they cause.[3,7-16] Psychophysical experiments are often affected by several factors, such as instructions to subjects, apparatus, room acoustics of a laboratory, etc. Therefore, it is not easy to compare the results from different laboratories. The authors, who belong to different research institutes, made a plan to do joint experiments using the same stimuli, the same instruction, and the similar type of equipment, and tried to make clear the appropriate method for evaluating impulsive noises. The authors have continued participating in cooperative studies for finding a solution to this problem since 1982. An experiment on loudness of single bursts of impulsive sound was the first step in the round robin test.[3] The results of the experiment reveal that both L_{pE} (to be discussed later) and the maximum output of an r.m.s. circuit with a time constant of 125 ms or 1 s can explain the loudness of a single burst of impulsive sound which has a quick onset (1 ms for 20 dB change), a steady part (0～100 ms duration) and a trailing part (30～300 ms for 20 dB change).

Table 1 The names of the laboratories and the researchers that participated in the round robin test.

Laboratories	Affiliated reseachers
Muroran Inst. Technol. (Dept. Archit.)	Izumi, Kiyoto
Tohoku Univ. (Res. Inst. Electr. Commun.)	Sone, Toshio Suzuki, Yōiti Ogura, Yasunori Kono, Shunichi
Sendai Natl. Coll. Technol. (Dept. Electron. Eng.)	Kumagai, Masazumi
Electrotech. Lab. (Lab. Acoust.)	Miura, Hajime Kado, Hisashi
Univ. Tokyo (Inst. Ind. Sci.)	Tachibana, Hideki
Kyoto Univ. (Fac. Eng.)	Hiramatsu, Kozo
Osaka Univ. (Coll. Gen. Educ.)	Namba, Seiichiro Kuwano, Sonoko
Osaka Univ. Arts	Kitamura, Otoichi
Kyushu Inst. Des. (Dept. Acoust. Des.)	Sasaki, Minoru
Kumamoto Univ. (Dept. Electr. Eng. Comput. Sci.)	Ebata, Masanao
Kumamoto Univ. (Dept. Environ. Constr. Eng.)	Yano, Takashi

The experiment discussed here was carried out on repeated impulsive sounds. We actually experience repeated impact sounds such as noise from a diesel pile hammer, a concrete breaker, a typewriter or a helicopter.[16] In order to clarify whether the same method of evaluation used with a single burst of impulsive noise is applicable to a repeated burst or not, we designed an experiment to measure loudness and noisiness of repeated impulsive sounds.

Table 1 shows the names of the eleven laboratories with which the authors are affiliated.

2. LOUDNESS OF REPEATED IMPULSIVE SOUNDS

2.1 Experimental Procedure

The constant method was used here in psychoacoustical experiments for both loudness and noisiness of impulsive sounds.

Table 2 describes the test stimuli used in the experiment where their levels are expressed in terms

Table 2 Experimental conditions and the levels measured in different ways.

Data No.	Peak level (phon)	Rise time*1 (ms)	Decay time*1 (ms)	Repetition rate (times/s)	Evaluated levels by several evaluating methods*2 (dB)			
					L_{pE}	I	F	S
1	85	1	30	single burst	62.1	76.2	71.6	63.2
2				1	66.9	77.9	71.6	64.9
3				3	70.8	80.0	71.9	68.2
4				10	75.4	82.0	74.3	72.9
5				30	80.1	83.4	78.3	77.5
6			100	single burst	67.3	79.6	75.8	68.1
7				1	72.1	80.8	75.9	69.9
8				3	75.9	82.2	76.2	73.2
9				10	80.6	83.5	79.0	77.9
10				30	85.3	85.4	83.3	82.6
11			300	single burst	72.2	81.9	79.1	72.3
12				1	76.9	82.7	79.1	74.2
13				3	80.7	83.5	79.7	77.7
14				10	85.5	85.4	83.4	82.6
15				30	90.0	88.7	88.0	87.3

*1 The time with 20 dB change.
*2 Carrier signal is 1 kHz sinusoidal wave. L_{pE} is frequency-unweighted sound exposure level. I, F and S are the peak level through 'I,' 'F' and 'S' detector-indicator characteristic, respectively.

of loudness level. Figure 1 shows the envelopes of test stimuli which have exponentially rising and decaying parts. These forms were chosen on the basis of the analysis of actual impact sounds.[11] The stimuli were digitally synthesized by means of a 32-bit minicomputer (TOSBAC DS-600) in which a single burst of impulsive sound was superimposed on the original sound with some time delay to create a repetitive impulsive sound. When envelopes of bursts of impulsive sounds overlapped, they were synthesized based on the energy rule.

Figure 2 shows an example of the time pattern of a pair of stimuli consisting of a test stimulus and a comparison stimulus. In this figure, the durations of the test stimuli range between 2 and 3 s according to the decay time except for a stimulus of a single burst, since the time delay of the starting point of the last impulse was limited to 2.0 s from the beginning of the burst.

The carrier signals for stimuli were the same as those used in the previous experiment, i.e., a 1 kHz sinusoidal wave and a mixture of two asymmetric rectangular waves with fundamental frequencies of 440 Hz and 1,175 Hz.[3] The ratio of the amplitude of the 440 Hz component to that of the 1,175 Hz component was three to two. Both frequencies are in inharmonic relation and the amplitude ratio was chosen so as to bring about a fusion of both components. The duty cycle for the rectangular waves was 15% in order to reveal the wide frequency spectra. This complex signal will be hereafter referred to as the asymmetric rectangular wave.

The peak level of an impulse was 85 phon for both carrier signals. This level is the same as that for continuous sound having a peak level equivalent to that of an impulsive sound. It is equivalent to SPL, 85 dB in a 1 kHz sinusoidal wave and SPL, 82 dB in an asymmetric rectangular wave. This 3 dB

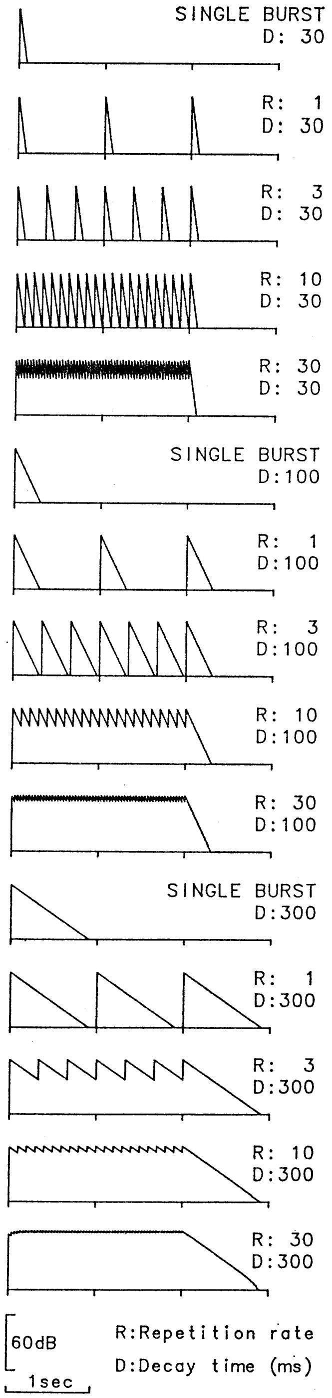

Fig. 1 The envelopes of the test stimuli. Rise and decay time is the time required for 20 dB change.

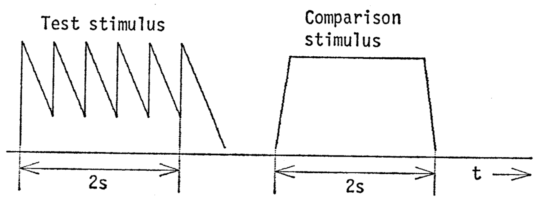

Fig. 2 The time pattern of the stimuli pair used in the test.

difference was subjectively obtained in a preliminary experiment. It should be noted that the maximum level of the synthesized envelope could be higher than 85 phon for test stimuli with the higher repetition rate and/or the longer decay time.

The comparison stimulus was a steady sound lasting 2 s, and its rise and decay time were both 5 ms for a 20 dB change in level. The carrier signal of the comparison stimulus was always the same as that of the test stimulus with which it was compared. The level of the comparison stimulus was one of nine levels which differed by a step of 2.5 dB. In the experiment both orders of stimulus presentation were randomized: 1) a test stimulus followed by a comparison stimulus, and 2) a comparison stimulus followed by a test stimulus. Since each pair of stimuli was presented to a subject three times, he/she responded to 54 pairs of stimuli for each stimulus condition.

The synthesized stimuli were produced by a 16 bits D/A converter at a sampling rate of 50 kHz and recorded on video tape in EIAJ format (44.056 kHz, 14 bits) of PCM code for distribution among the cooperating laboratories.

Our agreement upon experimental conditions were the following: 1) binaural hearing through headphones, 2) a subject sitting on a chair with his/her eyes closed during the experiment session, 3) background noise in a listening room less than 35 dB in A-weighted SPL, 4) a dead listening room, 5) a listening room in which there is enough light to read a book.

Headphones used in the experiments were YAMAHA HP-1000 manufactured in the same batch, and their frequency response characteristics were ascertained to be uniform beforehand. For the purpose of training subjects, a specially recorded tape was prepared. This tape contained combinations of stimuli which could be judged easily. The contents of the instruction given to subjects were prepared at

Osaka University, and it was basically the same as that used in the previous experiment. We simply asked subjects to judge which stimulus in a pair was louder (2AFC paradigm).

The experiments were executed between 1984 to 1985, and the detailed results were recorded on OCR (Optical Card Reader) sheets or floppy discs for collection. The subjects were 111 young adults with normal hearing.

2.2 Results on Loudness

Experimental results were first analyzed at Tohoku University. Two kinds of PSE (Point of Subjective Equality) averages were calculated from the data; one is the arithmetic mean of PSE's calculated for an individual subject, and the other is a PSE obtained from integrated data on the assumption that all responses of the subjects to stimuli are random samples from the same population. The former is called PSE(I) and the latter PSE(T) hereafter. PSE's were calculated by using the method of maximum likelihood estimation.[17]

Tables 3 and 4 show the frequency distribution of individual PSE's as well as the mean values (PSE(I)) and the standard deviations.

There were a few data which could not be processed by the method of maximum likelihood estimation. They were classified into two types: one was the type for which the psychometric function could not be fixed clearly because of the randomness of the responses, and the other was the type for which PSE's fell far outside the range of comparison stimuli prepared for the experiment. One subject's data belonging to the former type were discarded from loudness estimation due to his inability to discriminate the difference between two sounds. Regarding the latter type of data, almost all of the comparison stimuli were judged louder or softer than the test stimuli. Ten data out of the 3,270 were of the latter type for loudness, while about 9% of the data was found to be of this type for noisiness. The latter type of response was concentrated on the single burst of impulsive sound, and furthermore, most of the PSE's in these cases seemed to be below the lowest level of the comparison stimuli prepared. The number of this type of data is indicated by UL and UG in Tables 3 and 4. UL is the number of data in which almost all test stimuli were judged softer than the comparison stimuli irrespective of their level, while UG is the number of data in which almost all test stimuli were judged to be louder than the comparison stimuli.

Table 3 Frequency distribution of subjects whose PSE's for loudness are within the ranges. Carrier signal is 1 kHz sinusoidal wave. PSE (I) is an arithmetic mean of individual PSE. UL and UG are the frequencies of inestimable data because of one-sided judgment. The data for UL may have PSE's less than 50 phon, while the data for UG may have PSE's greater than 92 phon.

No.	–50	–52	–54	–56	–58	–60	–62	–64	–66	–68	–70	–72	–74	–76	–78	–80	–82	–84	–86	–88	–90	–92	–	UL	UG	PSE(I)	SD
1	1	1	0	0	1	1	2	5	14	15	16	19	12	12	4	3	0	0	0	0	0	0	0	4	0	69.3	5.2
2	0	0	0	0	1	0	0	0	7	11	10	27	22	16	7	6	3	0	0	0	0	0	0	0	0	72.1	4.0
3	0	0	0	0	0	1	0	0	0	1	1	17	20	26	19	18	6	1	0	0	0	0	0	0	0	75.1	3.4
4	0	0	0	0	0	0	0	0	0	0	1	0	3	12	26	35	21	9	3	0	0	0	0	0	0	78.7	2.6
5	0	0	0	0	0	0	0	0	0	0	0	0	0	4	5	20	36	29	11	3	2	0	0	0	0	81.4	2.6
6	0	0	0	0	0	0	0	0	0	7	4	11	13	25	25	15	6	0	3	0	0	0	0	1	0	75.2	3.8
7	0	0	0	0	0	0	0	0	0	1	0	2	8	19	22	27	21	7	3	0	0	0	0	0	0	77.9	3.2
8	0	0	0	0	0	0	0	0	0	0	0	0	2	2	15	29	33	25	4	0	0	0	0	0	0	80.2	2.5
9	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	10	22	47	26	4	0	0	0	0	0	82.7	2.0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	11	33	39	21	2	1	0	0	0	84.3	2.1
11	0	0	0	0	0	0	0	0	0	0	0	5	9	6	10	28	22	17	10	2	0	0	0	1	0	79.5	3.8
12	0	0	0	0	0	0	0	0	0	0	0	0	1	1	8	14	37	31	15	3	0	0	0	0	0	81.6	2.4
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14	38	48	7	3	0	0	0	0	84.0	1.8
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	21	53	24	6	0	0	0	0	85.1	1.7
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	14	55	34	5	1	0	0	87.5	1.6

Table 4 The same table as Table 3 except that the carrier signals are asymmetric rectangular waves.

No.	–50	–52	–54	–56	–58	–60	–62	–64	–66	–68	–70	–72	–74	–76	–78	–80	–82	–84	–86	–88	–90	–92	92–	UL	UG	PSE(I)	SD
1	0	0	1	1	0	1	0	6	7	9	25	16	16	17	3	3	1	0	0	0	0	0	0	4	0	70.3	4.6
2	0	0	0	0	0	1	0	1	6	2	13	16	26	23	15	6	1	0	0	0	0	0	0	0	0	72.7	3.8
3	0	0	0	0	0	0	0	0	0	2	2	7	22	30	20	21	6	0	0	0	0	0	0	0	0	75.5	2.9
4	0	0	0	0	0	0	0	0	0	0	0	0	1	8	25	32	26	15	3	0	0	0	0	0	0	79.4	2.4
5	0	0	0	0	0	0	0	0	0	0	0	0	1	1	4	31	37	27	8	1	0	0	0	0	0	80.9	2.2
6	1	0	1	0	0	0	4	0	1	1	2	6	8	13	27	27	19	0	0	0	0	0	0	0	0	75.8	5.8
7	0	0	0	0	0	0	0	1	0	0	0	1	6	14	18	32	28	9	1	0	0	0	0	0	0	78.4	3.1
8	0	0	0	0	0	0	0	0	0	0	0	1	0	2	7	31	34	22	11	1	1	0	0	0	0	80.9	2.5
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	20	62	22	3	0	0	0	0	0	83.0	1.6
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	23	54	21	5	0	0	0	0	84.9	1.8
11	0	0	0	1	1	0	1	0	0	0	0	6	2	3	14	16	27	25	14	0	0	0	0	0	0	79.6	5.1
12	0	0	0	0	0	0	0	0	0	1	0	0	0	0	7	17	31	32	15	6	1	0	0	0	0	81.8	2.9
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	22	38	36	6	2	0	0	0	0	83.4	2.1
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	44	42	14	2	0	0	0	86.2	1.6
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	22	70	13	0	0	0	88.5	1.3

Table 5 PSE(T) for loudness of repeated impact sound.

Decay time (ms)	Repetition rate (repetitions/s)	1 kHz sinusoidal wave (phon)	Asymmetric rectangular wave (phon)
30	single burst	69.4	70.0
30	1	72.1	72.7
30	3	75.2	75.5
30	10	78.6	79.3
30	30	81.3	80.9
100	single burst	75.2	76.3
100	1	77.9	78.4
100	3	80.3	80.9
100	10	82.7	83.0
100	30	84.2	84.8
300	single burst	79.5	80.0
300	1	81.6	81.8
300	3	83.9	83.3
300	10	85.1	86.2
300	30	87.5	88.4

Table 5 shows PSE(T)'s. Comparing this table with Tables 3 and 4, we can see that PSE(I) and PSE(T) are almost the same.

2.3 Discussion

Table 6 (a) shows the results of the analysis of variance of individual PSE's. The main sources for this analysis were the laboratories where experiments were executed (10), the carrier signals of stimuli (2), the decay times (3) and the repetition rates (5) of stimuli. Sex was not considered in the analysis because it was insignificant in the preliminary analysis. SPSS^{X} statistical package was used for this analysis. All the main sources were significant beyond 0.01 points. The results of multiple classification analysis (Table 6 (b)), however, show that the contributions of the laboratories (0.012) and the carriers (0.002) were low as compared with those of the decay times (0.336) and the repetition rates (0.348). Moreover, the maximum deviation among categories of the laboratories (about ± 1 dB) and the carriers (± 0.2 dB) were far lower than those of the decay times (± 4 dB) and the repetition rates (± 5 dB). Therefore, the influences of the laboratories and the carriers on the experimental results, though statistically significant, were considered to be small enough as their contributions and deviations were relatively small.

As a result of the previous experiment of the round robin test, we concluded that L_{pE} was appropriate for describing the loudness of a single burst of impulsive sound, where L_{pE} equals the frequency-unweighted sound exposure level as expressed by Eq. (1).[3,18] In this paper the relation between the experimental results and L_{pE} is examined as well.

Table 6 Result of analysis of variance and multiple classification analysis for loudness PSE(I).

(a) Result of analysis of variance.

Source of variation		Sum of squares	DF	Mean square	*F*
Main Effects		75,837.877	16	4,739.867	551.025
LABO		1,389.705	9	154.412	17.951**
CARRIER		174.982	1	174.982	20.342**
DECAY		36,630.753	2	18,315.376	2,129.221**
REPEAT		38,006.947	4	9,501.737	1,104.607**
2-way interactions		3,764.013	77	48.883	5.683
LABO	CARRIER	340.054	9	37.784	4.392**
LABO	DECAY	502.691	18	27.927	3.247**
LABO	REPEAT	1,937.037	36	53.807	6.255**
CARRIER	DECAY	2.948	2	1.474	0.171
CARRIER	REPEAT	27.727	4	6.932	0.806
DECAY	REPEAT	970.809	8	121.351	14.107**
Explained		79,601.889	93	855.934	99.505
Residual		27,233.661	3166	8.602	
Total		106,835.551	3259	32.782	

* Significant beyond 0.05 point.
** Significant beyond 0.01 point.

(b) Result of multiple classification analysis.
Grand mean=79.90

Variable+category	*N*	Deviation	Contribution ratio
LABO			0.012
1 MURORAN	180	−0.46	
2 TOHOKU	465	−0.06	
3 SENDAI	416	0.33	
4 ETL	390	1.14	
5 TOKYO	298	0.01	
6 KYOTO	252	−0.99	
7 OSAKA	300	−0.31	
8 KYUSHU	390	−0.05	
9 KUMAMOTO (E)	329	−0.95	
10 KUMAMOTO (A)	240	0.82	
CARRIER			0.002
1 SINE WAVE	1,614	−0.23	
2 RECT WAVE	1,646	0.22	
DECAY			0.336
1 30	1,082	−4.31	
2 100	1,089	0.45	
3 300	1,089	3.83	
REPEAT			0.348
1 SINGLE	644	−4.84	
2 1	654	−2.47	
3 3	654	−0.03	
4 10	654	2.62	
5 30	654	4.65	

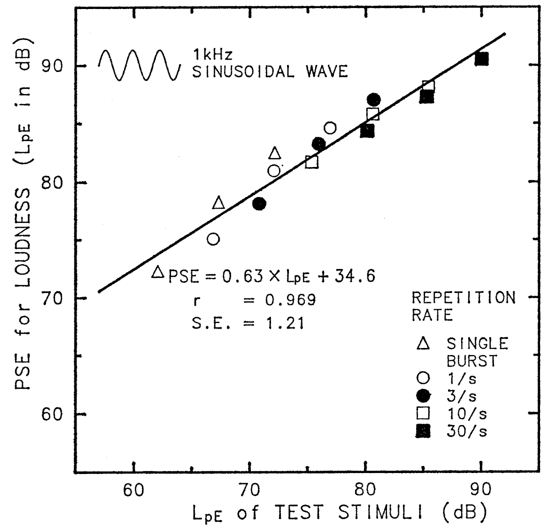

Fig. 3 Relation between L_{pE} of the test stimuli (abscissa) and their PSE's of the loudness (ordinate). L_{pE} means the level of the squared integral of sound pressure. In this figure, PSE's are PSE(I) that was an arithmetic mean of individual PSE's. This figure shows the results of the experiments in which the carrier of stimuli was a 1 kHz sinusoidal wave. The solid line is a regression line. 'r' is the correlation coefficient. 'S.E.' is the standard error of estimation.

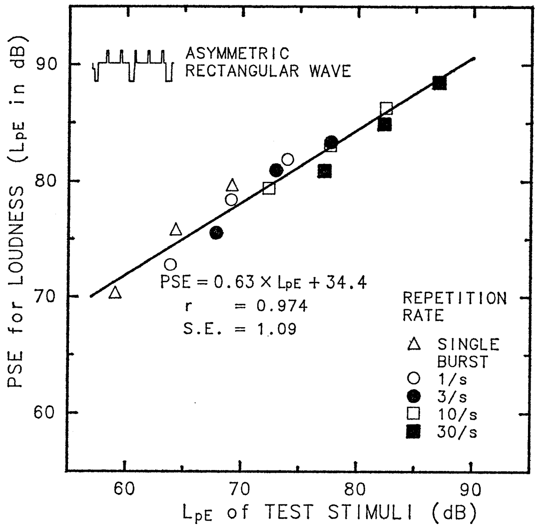

Fig. 4 The same relation as in Fig. 3 except that the carrier was the asymmetric rectangular wave.

$$L_{pE}=10\log\left[\frac{1}{T_0}\int_0^{\infty}\frac{p^2(t)}{p_0^2}dt\right] \qquad (1)$$

$T_0=1$ s, $p(t)$: sound pressure, $p_0=20\ \mu$Pa

Figures 3 and 4 show the relations between L_{pE} and PSE(I)'s. From these figures it can be seen that L_{pE} and PSE(I) are strongly correlated with each other. The regression coefficients of 0.63 and 0.62 in Figs. 3 and 4 mean that PSE increases by about 6 dB as L_{pE} increases by 10 dB. This result is thought to arise from the character of our auditory system, i.e., the auditory time window for loudness is shorter than the whole length of stimuli used.

Nevertheless, the strong correlation between L_{pE} and PSE's suggests that L_{pE} has the potential to be a descriptor of the loudness of repeated impulsive sounds used in our experiment, though some modification might be needed.

The correlation coefficients between experimental PSE(T)'s and L_{pE} are 0.969 (1 kHz sinusoidal carrier) and 0.968 (asymmetric rectangular carrier), and regression coefficients are 0.63 and 0.62. These values are much the same as those in PSE(I)'s.

As for the effects of carriers, we have concluded that the difference in frequency spectrum has little influence on the results as far as our experiment is concerned.

3. NOISINESS OF REPEATED IMPULSIVE SOUNDS

In this phase of the round robin test, the experiment on noisiness was also carried out to establish a method of evaluating impulsive noises from a rather practical point of view. This experiment was executed between late 1985 to early 1987.

3.1 Experimental Procedure

The experimental procedure was basically the same as that used in the experiment on loudness. The instruction used here was also the same as that used in loudness evaluation except that the word "loud" was replaced by "noisy." The instruction was reconsidered by co-workers of Osaka University.

Since there was an interval of more than several months after the loudness experiment was concluded, subjects were chosen irrespective of their experience in the previous experiment. The number of subjects was 109 (83 males and 26 females) for the sinusoidal carrier, and 101 (79 males and 22 females) for the asymmetric rectangular carrier. All were young adults with normal hearing.

3.2 Results on Noisiness

Two types of statistics, PSE(I) and PSE(T), were calculated again. Tables 7 and 8 show the frequency distributions of individual PSE's as well as their mean values (PSE(I)) and the standard deviations. Table 9 indicates PSE(T). A little difference is seen between PSE(I)'s and PSE(T)'s in the tables.

As mentioned in the previous section, there were some data from which PSE's could not be estimated. The actual number of this type of data was 270 out of 3,030 (8.91%). Two hundred and sixty of the 270 seemed to show that PSE's were far below the lowest level of comparison stimuli prepared. The remaining 10 data suggested, on the contrary, that PSE's were far greater than the highest comparison stimulus. These data have some effects in estimating PSE(T), although PSE(I) could not be obtained clearly. The data of eight subjects (three for sinusoidal wave and

Table 7 Frequency distribution of subjects whose PSE's for noisiness are within the ranges. Carrier signal is 1 kHz sinusoidal wave. PSE(I) is an arithmetic mean of individual PSE. UL and UG are the frequencies of inestimable data because of one-sided judgment. The data for UL may have PSE's less than 50 phon, while the data for UG may have PSE's greater than 92 phon.

No.	–50	50–52	52–54	54–56	56–58	58–60	60–62	62–64	64–66	66–68	68–70	70–72	72–74	74–76	76–78	78–80	80–82	82–84	84–86	86–88	88–90	90–92	92–	UL	UG	PSE(I)	SD
1	4	1	6	1	5	4	6	9	12	9	8	4	3	1	0	0	0	0	0	0	0	0	0	33	0	62.4	7.8
2	4	3	2	3	2	4	5	11	5	7	10	10	10	8	3	1	0	0	0	0	0	0	0	18	0	65.6	8.6
3	1	0	0	1	1	2	4	3	15	5	6	11	10	12	9	8	5	0	0	1	0	0	1	11	0	71.0	7.1
4	1	0	1	1	0	0	1	3	4	3	7	6	7	11	13	17	14	7	3	3	1	0	0	3	0	75.5	7.2
5	0	0	0	1	0	0	0	0	2	1	1	2	2	5	4	14	18	24	11	8	4	3	1	5	0	81.1	5.8
6	1	1	2	3	1	3	4	4	16	6	10	12	8	7	3	3	0	0	0	0	0	0	0	22	0	67.4	6.9
7	4	0	0	0	1	1	1	2	4	11	13	8	8	12	12	10	4	1	0	0	0	0	0	14	0	71.0	8.3
8	0	1	0	0	0	1	1	2	2	2	5	10	7	11	13	12	15	8	3	0	0	0	1	12	0	75.8	6.4
9	0	0	0	0	0	0	1	1	0	2	2	2	6	3	8	11	22	22	14	5	1	2	0	4	0	80.3	5.4
10	0	0	0	0	0	0	0	2	0	0	0	1	0	2	6	4	15	16	30	17	11	1	1	0	0	83.6	4.6
11	3	0	2	0	3	3	0	5	6	3	10	12	7	9	8	7	5	1	0	0	0	0	0	22	0	70.0	8.3
12	1	1	0	0	0	1	2	1	2	5	5	9	11	8	12	17	15	6	2	0	0	0	0	8	0	74.9	6.8
13	2	0	0	1	1	0	0	0	0	1	2	0	3	6	7	12	22	20	20	4	1	0	0	4	0	79.9	7.4
14	0	0	0	0	0	0	0	0	1	0	0	0	2	2	1	11	7	24	33	18	3	3	0	1	0	83.6	3.8
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	2	3	16	36	29	14	2	0	0	87.2	2.6

Table 8 The same table as Table 7 except that the carrier signals are asymmetric rectangular waves.

No.	–50	50–52	52–54	54–56	56–58	58–60	60–62	62–64	64–66	66–68	68–70	70–72	72–74	74–76	76–78	78–80	80–82	82–84	84–86	86–88	88–90	90–92	92–	UL	UG	MEAN	SD
1	2	3	1	2	4	5	0	7	7	11	8	3	2	0	1	1	0	1	0	0	0	0	0	38	0	64.0	7.4
2	0	1	5	4	3	8	0	7	10	10	10	5	15	3	3	4	0	1	0	0	0	0	0	7	0	66.6	7.4
3	0	0	1	0	0	2	9	0	2	11	5	9	13	10	4	14	3	3	1	1	0	0	1	5	2	72.3	7.0
4	0	0	0	0	0	0	2	0	1	0	2	3	5	9	14	20	11	8	11	5	2	0	0	0	3	79.0	5.4
5	0	0	0	0	0	0	0	0	1	0	0	0	3	4	8	10	20	21	11	10	5	1	0	0	2	81.9	4.3
6	1	6	2	2	4	3	4	1	8	4	8	8	9	6	5	2	3	1	0	0	0	0	0	19	0	67.1	8.9
7	0	2	0	3	0	1	3	12	1	0	8	10	11	9	8	9	7	2	1	0	0	0	0	9	0	71.5	7.8
8	0	1	1	0	1	1	3	0	1	2	0	4	8	16	7	13	12	12	4	6	1	1	0	1	1	77.1	7.6
9	0	0	0	0	0	0	0	0	0	0	3	0	2	0	4	8	24	23	18	4	9	0	0	0	1	82.3	4.1
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	14	40	20	14	2	1	1	0	85.8	2.2
11	1	0	1	2	1	5	2	3	5	0	15	3	11	4	7	8	6	2	3	0	0	0	0	17	0	71.1	8.3
12	0	0	0	0	1	0	1	0	2	4	0	10	7	12	5	13	12	12	8	3	1	0	0	5	0	77.5	6.2
13	0	0	0	0	0	1	0	0	0	1	2	0	1	2	7	13	22	24	13	5	3	1	0	1	0	81.4	4.5
14	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1	4	27	39	17	4	1	0	1	86.6	2.6
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	11	54	26	2	0	0	89.3	1.5

Table 9 PSE(T) for noisiness of repeated impact sound.

Decay time (ms)	Repetition rate (repetitions/s)	1 kHz sine wave (phon)	Asymmetric rectangular wave (phon)
30	single burst	61.9	61.7
30	1	67.3	67.7
30	3	72.3	73.3
30	10	77.4	80.2
30	30	82.1	82.5
100	single burst	68.0	68.1
100	1	72.9	73.5
100	3	76.9	78.9
100	10	81.5	83.3
100	30	84.7	85.8
300	single burst	71.0	71.9
300	1	76.4	77.8
300	3	81.5	82.5
300	10	84.3	85.9
300	30	87.6	89.2

five for asymmetric rectangular wave) were of the type for which the psychometric function could not be fixed clearly because of the randomness of the responses. Thus, these data were discarded from noisiness estimation.

3.3 Discussion on Noisiness

Table 10 shows the results of the analysis of variance and the multiple classification analysis of individual PSE's. All the main sources were significant beyond the 0.01 point, as well. Contributions were 0.036 for the laboratories, 0.006 for the carriers, 0.109 for the decay times and 0.436 for the repetition rates. The maximum deviation among categories were ± 3 dB for the laboratories, ± 0.8 dB for the carriers, ± 4 dB for the decay times, ± 9 dB for the repetition rates. The influences of the carriers on the experimental results, though statistically significant, were considered to be small enough as the contribution and the deviation of the carriers were relatively small. On the other hand, the maximum deviation among the laboratories was fairly large. However, as shown in the right most column of Tables 3 and 4, the standard deviation of PSE among the subjects was larger than the deviation among the laboratories. Thus we attribute the marked increase of the deviation in PSE of noisiness among

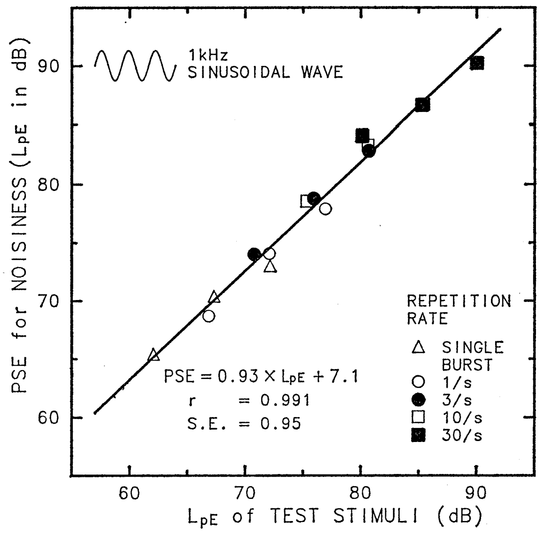

Fig. 5 Relation between L_{pE} of the test stimuli (abscissa) and their PSE's of the noisiness (ordinate). L_{pE} means the level of the squared integral of sound pressure. In this figure, PSE's is PSE(I) that was an arithmetic mean of individual PSE's. This figure show the results of the experiments in which the carrier of stimuli was a 1 kHz sinusoidal wave. The solid line is a regression line. '*r*' is the correlation coefficient. 'S.E.' is the standard error of estimation.

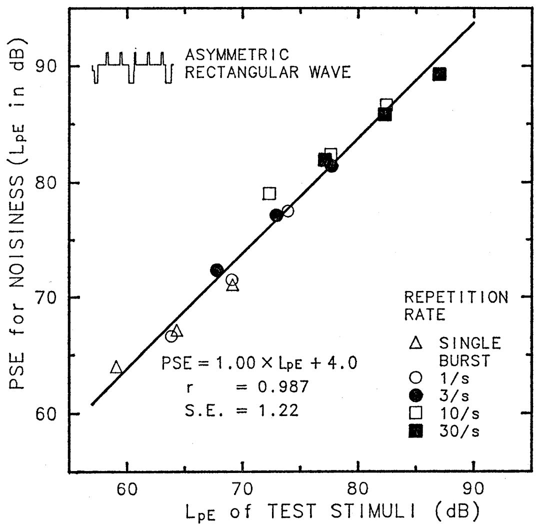

Fig. 6 The same relation as in Fig. 5 except that the carrier was the asymmetric rectangular wave.

Table 10 Result of analysis of variance and multiple classification analysis for noisiness PSE(I).

(a) Result of analysis of variance.

Source of variation		Sum of squares	DF	Mean square	F
Main effects		151,342.493	15	10,089.500	314.892
LABO		13,285.825	8	1,660.728	51.831**
CARRIER		1,993.964	1	1,993.964	62.231**
DECAY		30,426.362	2	15,213.181	474.802**
REPEAT		113,258.999	4	28,314.750	883.701**
2-way interactions		7,808.645	70	111.552	3.482
LABO	CARRIER	916.101	8	114.513	3.574**
LABO	DECAY	1,091.919	16	68.245	2.130**
LABO	REPEAT	4,735.219	32	147.976	4.618**
CARRIER	DECAY	156.710	2	78.355	2.445
CARRIER	REPEAT	268.719	4	67.180	2.097
DECAY	REPEAT	771.031	8	96.379	3.008**
Explained		159,151.138	85	1,872.366	58.436
Residual		85,325.469	2,663	32.041	
Total		244,476.607	2,748	88.965	

* Significant beyond 0.05 point.
** Significant beyond 0.01 point.

(b) Result of multiple classification analysis.
Grand mean=76.80

Variable+category	N	Deviation	Contribution ratio
LABO			0.036
1 MURORAN	190	0.43	
2 TOHOKU	200	2.13	
3 SENDAI	303	−0.56	
4 ETL	589	0.04	
6 KYOTO	200	−0.72	
7 OSAKA	251	0.49	
8 KYUSHU	313	3.00	
9 KUMAMOTO (E)	473	−3.06	
10 KUMAMOTO (A)	230	0.73	
CARRIER			0.006
1 SINE WAVE	1,422	−0.72	
2 RECT WAVE	1,327	0.77	
DECAY			0.109
1 30	878	−4.01	
2 100	921	−0.01	
3 300	950	3.72	
REPEAT			0.436
1 SINGLE	451	−9.56	
2 1	540	−5.29	
3 3	568	−0.44	
4 10	593	4.37	
5 30	597	8.08	

laboratories over the deviation in PSE of loudness to the large variance of PSE among subjects rather than to the difference of experimental conditions among the laboratories.

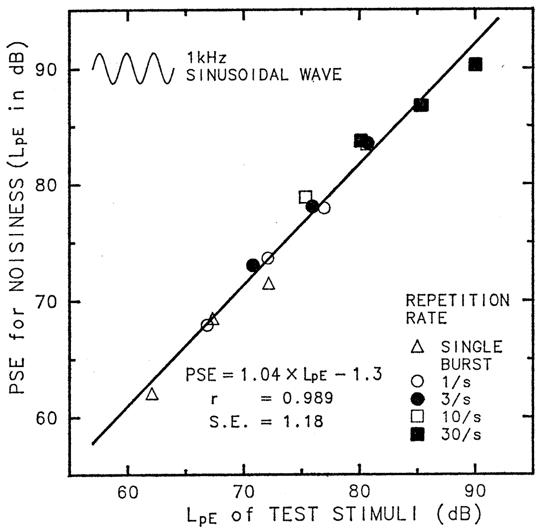

Fig. 7 The same relation as in Fig. 5 except that PSE's were PSE(T)'s. PSE(T) is a mean of the distribution from accumulated judgments of all the subjects, assuming that the all the 2 AFC responses of the subjects are samples from a certain normal distribution.

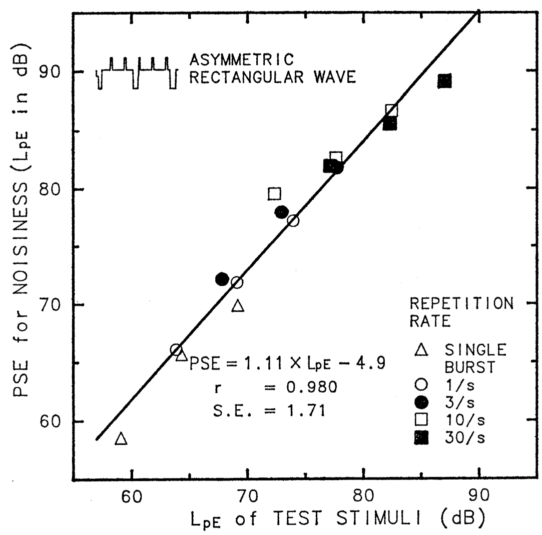

Fig. 8 The same relation as in Fig. 7 except that the carrier was the asymmetric rectangular wave.

Figures 5 and 6 indicate the relations between L_{pE} and PSE(I), while Figs. 7 and 8 show the relations between L_{pE} and PSE(T). The correlation coefficients between L_{pE} and PSE(I) are 0.991 and 0.987 for the sinusoidal and the asymmetric rectangular carriers, respectively, and those between L_{pE} and PSE(T) are 0.989 and 0.980, respectively. From these values, a strong correlation was found between L_{pE} and PSE in this case as well. The regression coefficients are 0.93 (1 kHz sinusoidal wave) and 1.00 (asymmetric rectangular wave) for PSE(I), while those for PSE(T) are 1.04 and 1.11. These values are significantly greater than those for loudness, and close to 1.0, which suggests that L_{pE} is more suitable for describing noisiness.

3.4 Comparison of Noisiness with Loudness

The standard deviations of the individual PSE's for noisiness (see Tables 7 and 8) is generally greater than those for loudness (see Tables 3 and 4). Furthermore, the number of data from which we could not estimate PSE's came to 9% for noisiness. These facts seem to show that the noisiness judgment is influenced by more complex factors than in the case of loudness judgment.

Regarding the coefficients for linear regressions of PSE on L_{pE}, those coefficients were $0.62 \sim 0.63$ for loudness, while they were $0.93 \sim 1.11$ for noisiness. This fact seems to indicate that the time constant for integration of sensation is longer for noisiness than for loudness, i.e., the difference in regression coefficients between loudness and noisiness can be explained by the difference in the length of an auditory time window.[19-22]

In any case, L_{pE} showed a high correlation with PSE obtained by our experiments, and thus loudness of repeated impulsive sounds whose duration is at most 3 s might be described by L_{pE} with some modification, and noisiness can be expressed by L_{pE} with minor modification.

4. CONCLUSION

The present paper has discussed the results of the second stage of experiments of a round robin test on the evaluation of impact sounds. Two psychological attributes, loudness and noisiness, were dealt with in this study. The PSE's for both attributes were obtained by using the same experimental procedure.

The results of the study are summarized as follows:

1) Loudness

a) Correlation between PSE and L_{pE} is high.

b) Regression coefficients of PSE on L_{pE} are about 0.6 which shows that the increase in loudness level is less than that in sound energy level.

c) From the above results it is seen that L_{pE} might be used with some modification for describing loudness of repeated impact sounds that are at most 3 s long.

2) Noisiness

a) Correlation between PSE and L_{pE} is high.

b) Regression coefficients of PSE on L_{pE} are close to 1.0.

c) From the above results it is seen that L_{pE} could be suitable for describing noisiness of repeated impact sounds that are 3 s at most.

3) The difference between results of carrier signals used in this study has little effects on the experimental data.

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REFERENCES

1) ISO 1996/1-1982, "Description and measurement of environmental noise, Part 1: Basic quantities and procedures" (1982).
2) S. Namba and S. Kuwano, "Psychological study on L_{eq} as a measure of loudness of various kinds of noises," J. Acoust. Soc. Jpn. (J) **12**, 774–785 (1982) (in Japanese).
3) T. Sone, Y. Suzuki, M. Kumagai, and T. Takahashi, "Loudness of a single burst of impact sound: Results of round robin test in Japan (I)," J. Acoust. Soc. Jpn. (E) **7**, 173–182 (1986).
4) ISO R 1996, "Assessment of noise with respect to community response" (1971).
5) ISO/DIS 1996/2, "Description and measurement of environmental noise, Part 2: Acquisition of data pertinent to land noise" (1985).
6) IEC Pub. 651, "Sound level meters" (1979).
7) ISO/TC 43/SC 1/SG B 10, "Instruction to the participants in Round Robin Test on evaluation of loudness level of impulsive noise arranged by study group B under ISO/TC 43/SC 1" (1970).
8) E. C. Daniel, S. Menad, F. Alain, and L. Frederic, "CEC Joint Project on Impulse Noise: Physical characterization and detection," Proc. Inter-Noise **85**, 897–900 (1985).
9) S. Kuwano and S. Namba, "On the dynamic characteristics of hearing and the loudness of impulsive sounds," Tech. Rep. Noise Acoust. Soc. Jpn. **N-8303-13**, 79–84 (1983) (in Japanese).
10) S. Kuwano, S. Namba, H. Miura, and H. Tachibana, "Evaluation of the loudness of impulsive noises using sound exposure level (L_{AE}) based on the results of a round robin test in Japan," Proc. Inter-Noise **84**, 809–814 (1984).
11) M. Kumagai, M. Ebata, and T. Sone, "Effect of some physical parameters of impact sound on its loudness (A study on the loudness of impact sound. I)," J. Acoust. Soc. Jpn. (E) **2**, 15–26 (1981).
12) S. Kuwano, S. Namba, and T. Kato, "The loudness of impulsive sound," J. Acoust. Soc. Jpn. (J) **34**, 316–317 (1987) (in Japanese).
13) M. Kumagai, M. Ebata, and T. Sone, "Comparison of loudness of impact sounds with and without steady duration (A study on the loudness of impact sound. II)," J. Acoust. Soc. Jpn. (E) **3**, 33–40 (1982).
14) M. Kumagai, M. Ebata, and T. Sone, "Loudness of impact sound with wide-band spectrum (A study on the loudness of impact sound. III)," J. Acoust. Soc. Jpn. (E) **3**, 111–118 (1982).
15) T. Sato and K. Izumi, "Experiments on the perceived noisiness of repetitive impulses," J. Acoust. Soc. Jpn. (J) **38**, 609–618 (1982) (in Japanese).
16) M. Kumagai, Y. Suzuki, and T. Sone, "The loudness of repeated impact sound (A study on the loudness of impact sound. IV)," J. Acoust. Soc. Jpn. (E) **3**, 231–237 (1982).
17) Y. Ogura, Y. Suzuki, and T. Sone, "Some consideration on the application of maximum likelihood estimation to experimental results obtained by constant method," Tech. Rep. Hearing Acoust. Soc. Jpn. **H-85-20** (1985) (in Japanese).
18) H. Tachibana, S. Ishizaki, and K. Yoshida, "A method of evaluating the loudness of isolated impulsive sounds with narrow frequency components," J. Acoust. Soc. Jpn. (E) **8**, 29–38 (1987).
19) B. Scharf, "Loudness," *Handbook of Perception IV*, ed. by E. C. Carterette and M. P. Friedman (Academic Press, New York, 1978), Chap. 6, pp. 204–209.
20) K. D. Kryter, *The Effects of Noise on Man*, 2nd ed. (Academic Press, New York, 1985), pp. 140–141.
21) K. Hiramatsu, K. Takagi, and T. Yamamoto, "The effect of sound duration on annoyance," J. Acoust. Soc. Jpn. (J) **32**, 739–750 (1976) (in Japanese).
22) S. Kuwano, S. Namba, and Y. Nakajima, "On the noisiness of steady state and intermittent noises," J. Sound Vib. **72**, 87–96 (1980).