Dependency of subjective loudness on the distribution of the sound pressure level of environmental noise

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Abstract: In this study, we investigated the influence of the distribution of sound-pressure levels (SPLs) on subjective loudness of environmental noise. To investigate the influence, subjective-loudness evaluation test was performed using road-traffic noise having various distributions of SPL. Skewness was used to evaluate the SPL distribution. Our results show that the loudness of the presented sound was perceived to be softer when the skewness was largest at 0.8 (the frequency of low SPL was high), even though the equivalent continuous A-weighted sound-pressure level ($L_{Aeq}$) was almost the same for all samples. On the other hand, the subjective loudness did not change significantly in the other conditions (the frequency of low SPL was low). From the result, the subjective loudness was found to decrease at a specific condition when the frequency of low SPL is high.

Keywords: Loudness, Environmental noise, Skewness, Road-traffic noise, Memory, Frequency

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1. INTRODUCTION

Controlling environmental noise at acceptable levels is important for living comfortably. To control environmental noise, it is necessary to set and follow an appropriate environmental noise evaluation index and to take additional measures such as reducing the level of sound from vehicles and installing sound-insulation barriers. The equivalent continuous A-weighted sound-pressure level ($L_{Aeq}$) is currently the standard environmental noise evaluation index. This index is useful because it can be obtained easily. Some studies, however, have reported that it does not express accurately the sensations of human beings in response to the frequency characteristics of environmental noise, but no other suitable evaluation indexes for environmental noise evaluation have yet been developed [1–4]. In considering a suitable index for environmental noise, in addition to considering the influence of the frequency characteristics, the effect of the duration of the noise on its subjective loudness should be considered, because environmental noise is typically evaluated over a particular period of time.

There have been many studies that have considered the subjective loudness for noise of a particular duration [5–11]. Hellbruck [7] performed a subjective-loudness evaluation test using environmental noise of 20 min duration (long-term noise) and of 30 s duration (short-term noise). The results showed that the long-term noise was perceived to be louder than the average of the subjective loudness of the short-term noise. Similar tendencies were observed in other previous studies [5,6]. These studies also reveal the effect of memory: a loud sound is remembered if it has sufficient duration, but soft sounds are forgotten. However, another study reported that not only loud sounds could be memorized, but other sounds could also be remembered, depending on their content [9].

Fastl et al. used a laboratory study to investigate the subjective loudness of road- and rail-traffic noise and found that rail-traffic noise was perceived as being softer than road-traffic noise, even though both types of noise had the same $L_{Aeq}$ (this effect was termed the railway bonus) [12–18]. They posited that the differences in the frequency characteristics of these two types of environmental noise accounted for the railway bonus [15,16]. We investigated the subjective loudness of road- and rail-traffic noise of particular durations by using a subjective-loudness evaluation test [11]. Our results show that the subjective loudness of environmental noise is found to decrease when the frequency of low sound-pressure level (SPL) was high in the SPL distribution, and this tendency was considered to be a factor in the railway bonus [11]. However, the situation when the subjective loudness decreases depending

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on the SPL distribution was unknown in the previous study. This means it is unknown when we have to take into account the influence of the SPL distribution on the loudness for assessment of the environmental noise.

In this study, we performed a subjective-loudness evaluation test using road-traffic noise with various SPL distributions in order to clarify the condition when the SPL distribution affects the subjective loudness significantly.

2. QUANTIFICATION OF SPL DISTRIBUTION FOR ENVIRONMENTAL NOISE

In this study, we investigated the influence of the SPL distribution on the subjective loudness of environmental noise. We performed a subjective-loudness evaluation test using environmental noise with various SPL distributions in order to clarify the condition when the SPL distribution affects the subjective loudness significantly.

2.1. Skewness Range in Environmental Noise

In order to determine a suitable parameter for the noise sample to be used in the subjective evaluation test, we first investigated the range of skewness in environmental noise. We recorded 10 min samples of road- and rail-traffic noise, each at four different locations near a road and near a rail, respectively. We then calculated the SPL distribution using $L_{Aeq}$ at each 10 s ($L_{Aeq,10s}$) and calculated skewness of the distribution in each noise sample. Figure 2 shows the distribution and skewness of a road-traffic noise sample. Applying this process to all the samples, we found that the skewness of the four road-traffic noise samples were in the range $-0.6$ to $-0.4$ (the frequency of low SPL is low), and the range of the skewness of the rail-traffic samples were from 0.3 to 0.8 (the frequency of low SPL is high). The target parameters for the sounds to be presented in the subjective evaluation test were based on the above ranges.

3. EXPERIMENT

In the subjective-loudness evaluation test, using binaural headphones, participants listened to road-traffic noise for 10 min and then evaluated its loudness.

3.1. Stimuli

To investigate the influence of the SPL distribution, we performed a subjective-loudness evaluation test using five road-traffic noise having various degrees of skewness at the same $L_{Aeq}$. Here, only road-traffic noise were used in this study to investigate the influence of skewness except for an influence of impression difference to sound source between

$$S_k = \frac{\sum(x_i - \bar{x})^3}{N\sigma^3} \quad (1)$$

Here, $N$ and $\sigma$ denote the sample number and the variance, respectively. When the distribution is skewed to left side, the skewness becomes positive. This means the frequency of low SPL in the distribution is high as shown in Fig. 1(a). When the distribution is Gaussian, the skewness becomes zero (Fig. 1(b)). When the skewness is negative, the distribution is skewed to the right side, and the frequency of low SPL in the distribution is low as shown in Fig. 1(c).

A subjective-loudness evaluation test was performed using road-traffic noise with various levels of skewness; the results are presented in the next section.

![Fig. 1 Skewness of the distribution.](image1)

![Fig. 2 SPL distribution and skewness of a road-traffic noise sample.](image2)
road- and rail-traffic noise [11]. The skewness range was set by referring skewness range of the recorded road- and rail-traffic noise because road-traffic noise has a possibility to have wider SPL distribution depending on the traffic volume. The target $L_{Aeq}$ for all road-traffic noise samples was set at a constant value of 65 dB, and the target skewness of the road-traffic noise samples were set at $-0.8$, $-0.4$, $0$, $0.4$, and $0.8$, respectively. Hence, five different kinds of target sounds were used in the test. The target parameters are shown in Table 1; note that the standard deviation of the SPL distribution was set at a constant value of 8 dB in all sound samples.

For the sounds to be presented in the test, five road-traffic noise samples were recorded for 10 min each at a height of 150 cm, each at a different location at the side of a road. The presented road-traffic noise samples were recorded using binaural headset microphones (HEAD Acoustics: SQuadriga). The values of $L_{Aeq}$, skewness, and standard deviation for the recorded 10 min samples of road-traffic noise are shown in Table 2.

As shown in Table 2, the parameters of the environmental noise samples did not meet the target values for the presentation. Therefore, the amplitudes of parts of each of the samples was modified so that it would meet the target values of $L_{Aeq}$, skewness, and standard deviation at the presentation from headphones. In the modification process, we attempted to adjust the skewness of each sound to within $\pm 0.1$ of the target value, $L_{Aeq}$ to within $\pm 1$ dB of the target value, and the standard deviation to within $\pm 1$ dB of the target value. The values of skewness, $L_{Aeq}$, and standard deviation for the modified samples at the presentation from headphones are shown in Table 3.

![Fig. 3](image-url) Variation of sound pressure level of road-traffic noises in presentation duration.

As shown in this table, the parameters for all the sound samples to be presented in the test met with the target values. Figures 3(a), (b), and (c) show the time variations of the SPL in Road 1 ($Sk. = -0.84$), Road 5 ($Sk. = -0.01$), and Road 4 ($Sk. = 0.80$), respectively. As shown in the figure, the frequency of the low SPL is found to increase according to the increase of the skewness. In addition, when the skewness is maximum at 0.8, a vehicle or a group of vehicles generating noise over 60 dBA SPL pass one time in a few decades of seconds as shown in Fig. 3(c).

### 3.2. Procedure and Participants

For the subjective evaluation test, the five road-traffic noise samples were saved on a personal computer (PC). One noise sample was selected randomly from the five samples and presented to the experimental participant via headphones (Sennheiser: HD600) through a playback system (HEAD acoustics: PEQ 5). After the presentation of the 10 min road-traffic noise sample, the participant evaluated the overall loudness in prepared categories. Seven major categories “very soft,” “soft,” “relatively

### Table 1 Target $L_{Aeq}$, skewness (Sk.), and standard deviation of SPL (S.D.).

| Sound | $L_{Aeq}$ (dB) | Sk.  | S.D. (dB) |
|-------|---------------|------|-----------|
| Road 1| 65.0          | -0.8 | 8.0       |
| Road 2| 65.0          | -0.4 | 8.0       |
| Road 3| 65.0          | 0.4  | 8.0       |
| Road 4| 65.0          | 0.8  | 8.0       |
| Road 5| 65.0          | 0.00 | 8.0       |

### Table 2 $L_{Aeq}$, skewness, and standard deviation of recorded sound samples.

| Sound | $L_{Aeq}$ (dB) | Sk.  | S.D. (dB) |
|-------|---------------|------|-----------|
| Road 1| 73.3          | -0.73| 7.7       |
| Road 2| 74.0          | -0.43| 7.0       |
| Road 3| 74.3          | -0.62| 7.3       |
| Road 4| 73.2          | -0.52| 7.5       |
| Road 5| 72.9          | -0.20| 5.9       |

### Table 3 $L_{Aeq}$, skewness, and standard deviation of SPL after amplitude modification for presentation.

| Sound | $L_{Aeq}$ (dB) | Sk.  | S.D. (dB) |
|-------|---------------|------|-----------|
| Road 1| 65.1          | -0.84| 8.9       |
| Road 2| 65.0          | -0.39| 7.1       |
| Road 3| 65.0          | 0.37 | 8.0       |
| Road 4| 65.0          | 0.80 | 9.0       |
| Road 5| 65.0          | -0.01| 7.1       |
soft,” “neither soft nor loud,” “relatively loud,” “loud,” “very loud” and four minor categories among each major category were prepared for the loudness evaluation [19]. In general, it is considered to be enough to prepare only the seven major categories for the evaluation of the loudness if the evaluated sound had a duration of a few decades of seconds and it did not change largely. However, the evaluated sound in this study had 10 min duration and it changed largely from quiet situation without any vehicles (40 dBA) to the situation with vehicles (80 dBA). Then, we considered using only the major categories may not be enough to investigate the influence of the frequency of the low SPL in the distribution (skewness) on the subjective loudness. Hence, four minor categories among the major categories were prepared. In total, 31 categories were prepared and the number from 1 to 31 was applied to each category from “very soft” to “very loud” for analyzing the experimental result.

In addition, short-term loudness evaluations were performed in 30 s intervals for the presentation duration of the road-traffic noise to check the participant’s consciousness of the presented sound. For the short-term evaluations, a timer on the PC monitor was used to inform the participant of the evaluation timing. In other words, timing was conveyed without presenting any additional sound. The short-term evaluation for 30 s was performed a total of 20 times for each samples of road-traffic noise having 10 min duration. The subjective loudness for short-term was evaluated using the same 31 categories as the evaluation of overall loudness for 10 min samples.

Thirteen males and one female, all in their 20’s and all having normal hearing ability, participated in the tests. Each participant evaluated the loudness of 20 short-term noises at 30 s intervals and evaluated the overall loudness for 10 min (a total of 21 evaluations for each participant per sample). The five samples of road-traffic noise with various degrees of skewness were each evaluated three times. Hence, a total of 15 tests (5 samples × 3 repeats) were performed for each participant, and a total of 210 tests (15 tests × 14 participants) were performed in total. As a result, 4,410 evaluations (21 evaluations × 210 tests) were performed in total.

3.3. Verification of Participants’ Evaluation Condition

Before analyzing the subjective overall loudness, we calculated the correlation between the subjective loudness and $L_{Aeq}$ for the short-term noise samples for each participant to check the participants’ evaluation condition. Figure 4 shows the correlation coefficient between the subjective loudness and $L_{Aeq}$ for the short-term noise samples for each participant.

The result shows the correlation coefficient for all participants over 0.7 and all participants were considered not to evaluate the loudness of the presented sounds for long duration (10 min) by guesswork. Hence, the evaluations of overall loudness, made by all participants, were used in the following analysis.

3.4. Loudness Dependency on Skewness

Figure 5 shows the average of the overall subjective loudness for all participants in each sound. The horizontal and vertical axes show the skewness and subjective loudness, respectively, and the error bars show the standard deviation of the subjective loudness.

As shown in Fig. 5, the subjective loudness was almost the same when the skewness was from −0.8 to 0 (low SPL frequency in the distribution is low) but the loudness was evaluated as smallest when the skewness was 0.8, even though these sounds had the same $L_{Aeq}$. This tendency, in which the subjective loudness was evaluated softer when the skewness was 0.8, was identical to that found in our previous study, where environmental noise having much low SPL frequency was perceived as softer [11]. Also, when the skewness was 0.4, the loudness was almost intermediate value between the loudness at skewness of 0 and 0.8.

To verify the difference of the subjective loudness on the skewness, analysis of variance (ANOVA) was performed. The result showed the probability $p$ of significance was 0.00 ($p \leq 0.05$). In addition, to verify the difference
of subjective loudness of each pair of presented sounds, a multiple-comparison analysis was performed. The result is shown in Table 4.

The result shows the differences of all pairs were not significant when the skewness were from −0.8 to 0.4 ($p > 0.05$), but the differences of all pairs between the sounds at skewness of 0.8 and the other sounds were significant ($p \leq 0.05$). Consequently, we did not find significant influence of the low SPL frequency on the subjective loudness when the frequency was low (skewness is from −0.8 to 0.4) but found the influence when the frequency was high (skewness is 0.8).

4. SUMMARY AND DISCUSSION

In this study, a subjective evaluation test using road-traffic noise with various SPL distributions in order to clarify the condition when the SPL distribution (frequency of the low SPL) affects the subjective loudness significantly. For the evaluation of the condition, skewness was applied as the indicator of the frequency of the low SPL in the distribution and the influence of skewness on the subjective loudness was investigated as the skewness was changed from −0.8 to 0.8 at the same $L_{Aeq}$ at 65 dB. The results show that when the skewness was from −0.8 to 0.4, the loudness did not change significantly, but when the skewness was 0.8, the subjective loudness became softer.

This tendency at the skewness of 0.8 is the same tendency that was obtained in previous studies [5–7,11]. However, the loudness did not change when the skewness was from −0.8 to 0.4. This is different tendency from that of the previous studies. The reason for this is considered to be related to the memory effect discussed in previous studies [5–7,11]. In this effect, after a period of hearing environmental noise, the louder sounds are remembered but the softer sounds are forgotten. This results after hearing the sound for a long time, and the influence of the louder sound increases in the evaluation of overall loudness. In the test used in this study, when the skewness was from −0.8 to 0.4, the impression of soft sounds may be lost after hearing a 10 min sample because the frequency of low SPL was not so high. As a result, the subjective loudness of these sounds was not changed because the participants only remembered the loud sounds. Thus, softer sounds in the presented sample had little influence on the subjective loudness at the condition. On the other hand, when the skewness is 0.8, the low SPL frequency was very high as shown in Fig. 3(c). In the condition, the participants may remember the softer sounds. As a result, the influence of the soft sounds on the perceived overall loudness might increase, and thus the subjective loudness might decrease.

Subsequently, we discuss the other influence of the presented sound characteristics on the subjective loudness except for the skewness. In this test, all presented sounds were road-traffic noise and having similar characteristic such as $L_{Aeq}$ and standard deviation of SPL distribution except for the skewness to evaluate the influence on the subjective loudness. However, the other characteristics of the sounds were not identical naturally because the presented sounds were not the same road-traffic noise. Therefore, the other characteristics of the sound except for the skewness might decrease the subjective loudness of Road 4 ($Sk. = 0.8$), that was evaluated softer in the subjective evaluation test. Then, we calculated $N_5$ loudness to evaluate the influence. The value was developed to evaluate the loudness of a time-varying sound like the sound presented in this study, considering various auditory perception characteristics except for the influence of skewness and the value has been reported to be able to express well the overall loudness [20]. We calculated $N_5$ for the five presented sound samples with various degrees of skewness that were used in this study. The relationship between the subjective loudness and $N_5$ is shown in Fig. 6.

As shown in the figure, the calculated loudness ($N_5$) of Road 4 was not calculated as softer comparing with the other sounds. This result indicates the characteristics of the presented sound except for the skewness rarely affect the subjective loudness of Road 4 as evaluated softer, and the skewness focused in this study is considered one of the major factors for the decrease of the loudness.
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