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A method to predict psychological response of noisiness to an acoustical stimulus with a prominent frequency component

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Abstract

This study experimentally evaluates a prediction method for the psychological response of the noisiness to a complex noise that includes a pure tone component. This paper first proposes the new psychological response prediction method, which is calculated by summing the point of subjective equality of the complex noise components as energy. The effectiveness of the proposed method is then examined using data obtained from indoor psychological experiments.

1. Introduction

The quantitative relationship between a physical noise stimulus and the psychological response is important in the field of noise control engineering. A fairly high correlation can be seen between an evaluation index based on energy, such as L_{Aeq}, and the psychological response to the noise [1–3]. A broadband noise that includes a prominent pure tone component, however, is perceived to be noisier than the broadband noise only, even though the two have the same L_{Aeq} value. That is, when a broadband noise includes a prominent pure tone component, the psychological response prediction based on the energy is underestimated. Therefore, some studies have not been able to substantially correlate an evaluation index, such as L_{Aeq}, and the psychological response [2,3]. Methods for predicting the psychological response to a noise based on energy have been investigated in previous studies [4–8]. However, the noise in these studies was limited to general broadband noise that did not incorporate a pure tone component. Because of this, the present study experimentally evaluates a prediction method for the psychological response to a complex

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noise that includes a pure tone component. Specifically, this study first proposes a new method for psychological response prediction that is determined using the total point of subjective equality (*PSE*), which is calculated as the sum of the complex noise components' energy. The effectiveness of the proposed method is then examined and evaluated using measured data from indoor psychological experiments.

2. Outline of psychological experiments

Two psychological experiments, Experiments I and II, were conducted to verify the effectiveness of the prediction method for the psychological response of the noisiness to a complex noise that includes a pure tone component. A description of the experiments is provided below.

2.1. Experiment I

The purpose of the first experiment was to investigate the relationship between the sound pressure level and the psychological response, for pure tone and narrowband noise cases. These results will be used as a basis for the psychological response prediction method.

2.1.1. Subjects

Eight college-age subjects with normal hearing, seven male and one female, were used in this experiment.

2.1.2. Acoustical stimulus

The following pure tone or narrowband noise was separately presented:

(A) *Pure tone*: Frequencies for the pure tone in the easy-to-audible frequency range were selected. The frequencies for the pure tone were chosen to be $f_1 = 1000$, $f_2 = 2000$, and $f_3 = 4000$ Hz. The pure tone was amplified or attenuated using random variables according to a uniform distribution (duration time: 5 s, dynamic range: [35, 65] dB).

(B) *Narrowband noise*: Band-limited white noises with center frequencies of $f_{c1} = 63$, $f_{c2} = 125, \ldots, f_{c8} = 8000$ Hz were amplified or attenuated using random variables according to a uniform distribution (duration time: 5 s, dynamic range: [35, 65] dB).

2.1.3. Measurement method

Seven categorized psychological impressions of the noisiness were adopted according to the method of continuous judgment by category [9]. These impressions were: $F1$: very calm, $F2$: quite calm, $F3$: slightly calm, $F4$: medium, $F5$: slightly noisy, $F6$: quite noisy, and $F7$: very noisy. Every 5 s, the subjects listened and judged their psychological impression. As they recorded their impressions in a computer, the sound pressure level was recorded. This process was repeated every 5 s for a total experiment duration of 5 min. This experiment was repeated four times for each pure tone and narrowband case.

2.2. Experiment II

The purpose of the second experiment was to compare the observed psychological response to the complex noise with the predicted response.

2.2.1. Subjects

The eight subjects used for Experiment I were also used for Experiment II.

2.2.2. Acoustical stimulus

A complex noise, which contained both a pure tone and a broadband noise, was produced as follows:

(a) *Pure tone*: The frequencies for the pure tone were $f_1 = 1000$, $f_2 = 2000$, and $f_3 = 4000$ Hz. The pure tone was amplified or attenuated using random variables according to a uniform distribution (duration time: 5 s, dynamic range: [35, 65] dB).

(b) *Broadband noise*:

(b.1) *Pseudo road traffic noise* (*with/without RC filter*): This broadband noise consisted of a pink noise with a spectrum closely resembling that of actual road traffic noise. The pseudo road traffic noise was amplified or attenuated using random variables according to a uniform distribution (duration time: 5 s, dynamic range: [35, 65] dB).

(b.2) *Real road traffic noise* (*with RC filter*): Road traffic noise was recorded at a roadside near a traffic signal (dynamic range: [41, 63] dB).

The time constant for the RC filter was $T = 3.75 \times 10^{-3}$ s [7].

2.2.3. Measurement method

The measurement methods in this experiment were the same as in Experiment I, however, the experiment was performed only once for each complex noise case.

3. Relationship between loudness level/sound pressure level and psychological response

The psychological response was found to more closely correspond with the loudness level standardized in ISO532B [10] than the L_{Aeq} value [2]. Fig. 1 shows the relationship between the loudness level LL_Z and the psychological response to a complex noise that is comprised of real road traffic noise (with RC filter) and a pure tone ($f_2 = 2000$ Hz). The "+" symbol in this figure represents the mean psychological response values when the ordinal scale F_i is used as an interval scale $F_i = i$. As can be seen in the figure, the LL_Z values and the psychological response correspond fairly well ($r = 0.8143$).

The relationship between the sound pressure level and the psychological response was obtained for each pure tone and narrowband noise case using Experiment I measured data. These relationships were used as a basis for the psychological response prediction to complex noise containing a pure tone component. The relationships between the sound pressure level of the pure tone and the psychological response for each frequency, $g_1(L; f_j)$ ($j = 1, 2, \dots, n$), and the relationships between the sound pressure level of the narrowband noise and the psychological response for each center frequency, $g_2(L; f_{ck})$ ($k = 1, 2, \dots, 8$) were established. The results for the

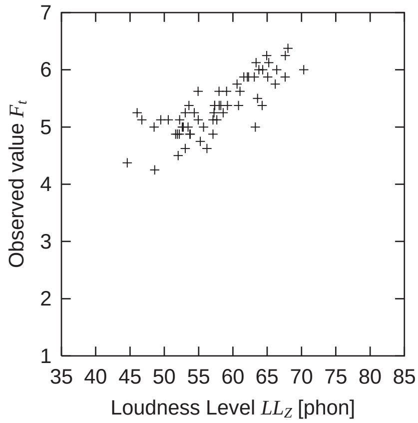

Fig. 1. Relationship between the loudness level and the psychological response ((a) pure tone ($f_2 = 2000$ Hz) and (b.2) real road traffic noise (with RC filter)).

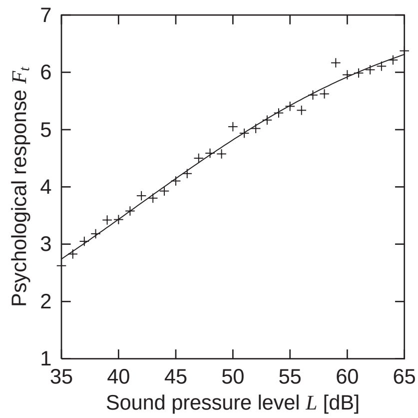

Fig. 2. Relationship between the sound pressure level and the psychological response ((A) pure tone; $f_1 = 1000$ Hz).

pure tone case ($f_1 = 1000$ Hz) are shown in Fig. 2. The solid line represents the regression function selected by Akaike information criterion (AIC) [11]. The logistic function was selected from a pool of three functions: a linear function, a logistic function, and a modified exponential function. Figs. 3 and 4 display the relationships between the sound pressure level and psychological response for pure tone and narrowband noise, respectively. The logistic function was selected by the AIC for all cases. It was observed that the sound became more ‘‘noisy’’ as the frequency increased for both the pure tone and the narrowband cases.

4. Psychological response prediction method

A proposed prediction method for the psychological response to a complex noise that includes a pure tone component is described below.

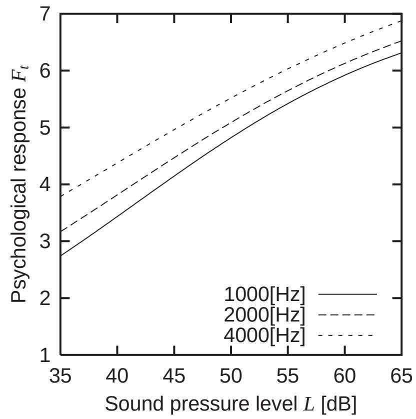

Fig. 3. Relationship between the sound pressure level and the psychological response ((A) pure tone).

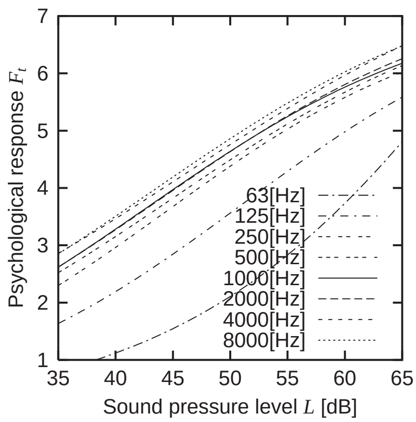

Fig. 4. Relationship between the sound pressure level and the psychological response ((B) narrowband noise).

(1) The standard stimulus is the pure tone ($f_1 = 1000$ Hz), and the standard function $g_s(L)$ is the relationship between the sound pressure level and psychological response $g_1(L;f_1)$ (Fig. 2).
(2) The PSE is obtained for each pure tone included in the complex noise:

$$PSE_{t,j} = g_s^{-1}(g_1(L_t;f_j)) \quad (j = 1, 2, \ldots, n). \tag{1}$$

(3) The PSE is obtained for each octave band of broadband noise that is included in the complex noise:

$$PSE_{t,k} = g_s^{-1}(g_2(L_t;f_{ck})) \quad (k = 1, 2, \ldots, 8). \tag{2}$$

(4) All of the PSE values obtained by Eqs. (1) and (2) are summed up as energy, and the total PSE value represents the PSE of the complex noise:

$$PSE_t = 10\log_{10}\left(\sum_{j=1}^{n} 10^{PSE_{t,j}/10} + \sum_{k=1}^{8} 10^{PSE_{t,k}/10}\right). \quad (3)$$

(5) The predicted value for the psychological response to a complex noise is obtained from the standard function $g_s(L)$:

$$F_t = g_s(x), \quad x = PSE_t. \quad (4)$$

(6) The average psychological impression to a fluctuating random complex noise can be obtained from the probability distribution function of PSE:

$$\langle F \rangle = \int_D g_s(x)p(x)\,\mathrm{d}x. \quad (5)$$

An interaction between two components depending on their frequency separation, such as beats, occurs sometimes. The additivity of the PSE in Eq. (3) only holds when there is no interaction between the two components. Currently, this premise is only a hypothesis. A systematic and rational noise evaluation method for variable complex noises that include a pure tone component has not yet been discovered. Nevertheless, considering the above hypothesis and conducting an experimental study of the noise evaluation method using the measurement data is considered valuable in the field of engineering. In the present study, the validity of the above hypothesis is checked during the initial stage.

5. Psychological response and impression

The relationship between PSE_t calculated in Eq. (3) and the psychological response for the complex noise containing real road traffic noise (with RC filter) and a pure tone ($f_2 = 2000$ Hz) for Experiment II is shown in Fig. 5. The predicted response PSE_t and the observed response

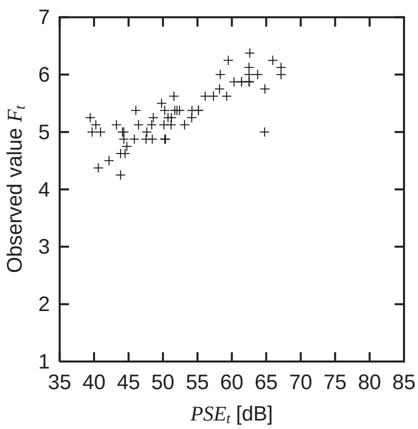

Fig. 5. Relationship between PSE and the psychological response ((a) pure tone ($f_2 = 2000$ Hz) and (b.2) real road traffic noise (with RC filter)).

coincided fairly well ($r = 0.8357$), as in the case of LL_Z. The proposed prediction method is advantageous because it simplifies the calculations needed for practical applications.

The observed psychological response to the complex noise contain broadband noise and pure tone in Experiment II was compared with the predicted values generated by the proposed method. Fig. 6 displays the comparison between the predicted and observed psychological response values for the case when the complex noise consists of road traffic noise (without RC filter) and a pure tone ($f_2 = 2000$ Hz). The results for the case with the complex noise consisting of real road traffic noise (with RC filter) and a pure tone ($f_2 = 2000$ Hz) is shown in Fig. 7. The predicted and observed psychological response values agree well. Although the results for the other cases are not displayed, their results are similar. Fig. 8 shows the comparison results between the predicted and observed values for the average psychological impression. The prediction error was found to be

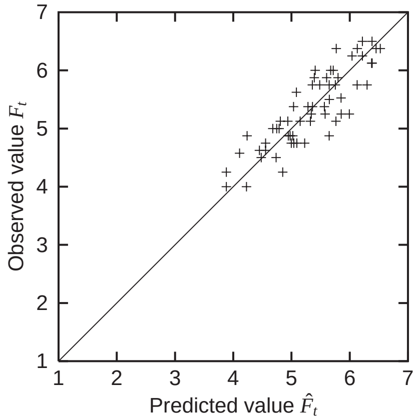

Fig. 6. Comparison between the predicted and observed values of the psychological response ((a) pure tone ($f_2 =$ 2000 Hz) and (b.1) pseudo road traffic noise (without RC filter)).

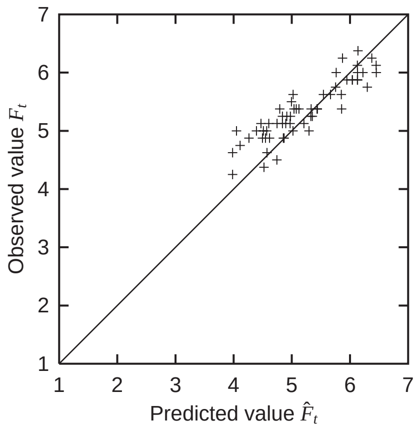

Fig. 7. Comparison between the predicted and observed values of the psychological response ((a) pure tone ($f_2 =$ 2000 Hz) and (b.2) real road traffic noise (with RC filter)).

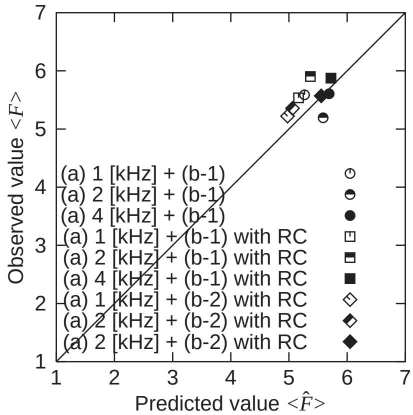

Fig. 8. Comparison between the predicted and observed values for the average psychological impression.

about half category, and the predicted values agree well with the observed ones for all cases. These results confirm that the hypothesis, the additivity of the PSE presented in Eq. (3), is valid. However, these results were generated in experiments where the two components had no interaction. In the future, the prediction method for the interaction case should be studied.

6. Conclusion

This study experimentally evaluates a prediction method for the psychological response to a complex noise that includes a pure tone component. The proposed method calculates the predicted value by summing the component PSE values of the complex noise as energy. The predicted psychological response to the total energy, PSE_t which was calculated by the proposed method, coincided fairly well with the observed psychological response, as in the case of LL_Z. The proposed method is advantageous because it requires only simple calculations. Because the predicted and observed psychological response values exhibited a good agreement, the effectiveness of the proposed method has been confirmed.

This study focused on a short-term response to noise. Future studies are needed to investigate a prediction method for a long-term impression that is based on short-term responses.

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