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Annoyance of noise stimuli in relation to the spatial factors extracted from the interaural cross-correlation function

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Abstract

While considering auditory–brain model for subjective responses, effects of spatial factors extracted from the interaural cross-correlation function (IACF) on annoyance of noise stimuli are examined. The previously developed indices to measure sound pressure levels (SPL) and frequency characteristics cannot fully explain the psychological effects of noise. In the first experiment, subjects judged their annoyance by changing fluctuations in the magnitude of interaural cross-correlation function (IACC) and the SPL. In the second, they judged their annoyance by changing fluctuations in the interaural time delay (τ_{IACC}) and the SPL. Results show that: (1) annoyance increased by increasing the fluctuations of IACC as well as the SPL, (2) annoyance increased by increasing the fluctuations of τ_{IACC} as well as the SPL.

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1. Introduction

The environmental noise has been evaluated according to sound pressure levels (SPL) and their frequency characteristics [1]. Noise criterion (NC) curves, the preferred noise criterion (PNC) curves and balanced noise criterion (NCB) curves have been developed to measure the SPL and its

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frequency characteristics [2–4]. Evaluations of temporal fluctuations, in both traffic and industry noise, have been made by utilizing the equivalent sound level (L_{eq}). These noise criteria did not include any of the spatial attributes of the sound field.

In a previous study, the spatial and temporal factors of the environmental noise to be measured have been proposed. For example, in a three-floor apartment, located in a quiet area, one resident was very annoyed that their sleep was disturbed by the noise of a toilet flushing upstairs. They accused the construction company of improper construction, even though the sound pressure level was only about 35 dBA. The construction company attempted to improve noise reduction in the bedroom. As a result, the SPL for the flushing toilet noise was improved by about 5 dBA. However, the residents were still annoyed by the noise. To investigate the reason as to why this flushing noise was so annoying, binaural measurements were conducted and the temporal and spatial factors of the sound field based on the model of the human auditory–brain system were analyzed [5]. The model consists of autocorrelators and an interaural cross-correlator for the analysis of sound signals arriving in both ears and specialization by human cerebral hemispheres. According to the model, temporal factors of sound signals are processed by the left hemisphere, while spatial factors of sound signals are processed by the right hemisphere [6–8]. Measurement of the noise made from the flushing toilet showed that the temporal and spatial factors changed dramatically as a function of time. This suggests that the flushing noise stimulated not only the right hemispheres but also the left hemisphere of the resident. This may explain why the resident felt such an annoyance. Both the temporal and spatial factors of aircraft and traffic noise [9,10] have already been measured.

The purpose of the present study is to investigate the effects of spatial factors extracted from the interaural cross-correlation function (IACF) on annoyance of noise stimuli in reference to the SPL. Dynamical effects of spatial moving sound images on the annoyance were investigated by means of simulating them in a testing room. The paired-comparison tests were conducted asking subjects which of the two noise stimuli was more annoying. The width of the sound image was fluctuated in the first experiment, and the horizontal direction of the sound image fluctuated in the second experiment.

2. Definition of the factors extracted from the IACF

The IACF between two sound signals at both ears $f_l(t)$ and $f_r(t)$ is defined by

$$\Phi_{lr}(\tau) = \frac{1}{2T}\int_{-T}^{+T} f'_l(t) f'_r(t+\tau)\,\mathrm{d}t, \quad |\tau| \leqslant 1.0\,\mathrm{ms}, \tag{1}$$

where $f'_l(t)$ and $f'_r(t)$ are obtained after passing through the A-weighted network, which corresponds approximately to the sensitivity of the ear, $s(t)$, so that $f'_{l,r}(t) = f_{l,r}(t)^* s(t)$.

The normalized IACF is defined by

$$\phi_{lr}(\tau) = \frac{\Phi_{lr}(\tau)}{\sqrt{\Phi_{ll}(0)\Phi_{rr}(0)}}, \tag{2}$$

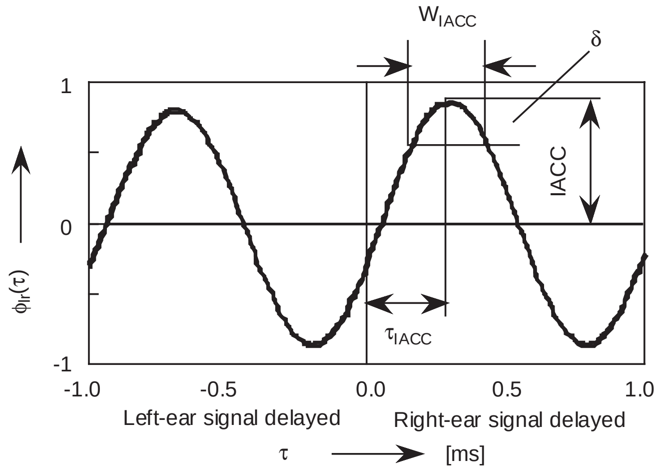

Fig. 1. Definition of the IACC, τ_{IACC}, W_{IACC} for the interaural cross-correlation function.

where $\Phi_{ll}(0)$ and $\Phi_{rr}(0)$ are the autocorrelation functions (ACFs) at $\tau = 0$ for the left and right ear, respectively. Independent factors extracted from the IACF are defined in Fig. 1. There are four significant factors:

1. The listening level given by denominator of Eq. (2), i.e., the geometrical mean of the sound energies arriving at both ears.
2. Magnitude of the interaural cross-correlation function IACC is defined by

   $$\mathrm{IACC} = |\phi_{lr}(\tau)|_{\max} \tag{3}$$

   for the possible maximum interaural time delay, say, $|\tau| < 1.0\,\mathrm{ms}$. The IACC is a significant factor in determining the apparent source width (ASW), the degree of subjective diffuseness and the subjective preference for the sound field [6].
3. Interaural delay time τ_{IACC}, at which the IACC is defined, is a significant factor for horizontal sound localization.
4. Width of the interaural cross-correlation function W_{IACC}, defined by the time interval between the δ-values below the IACC of the source signal, is a significant factor in determining ASW [7]. W_{IACC} greatly depends on the spectral content of the source signal.

3. Experiment 1: annoyance in relation to both SPL and IACC

3.1. Procedure

Annoyance judgments were performed by the paired-comparison method with changes in fluctuation of IACC and the SPL. The sound source was white noise. The moving sound images were simulated by the frontal direct sound (L_0) and two symmetrical lateral reflections (L_1 and L_2) in a soundproof chamber (Fig. 2). The loudspeakers were at the level of the subject's ears. To

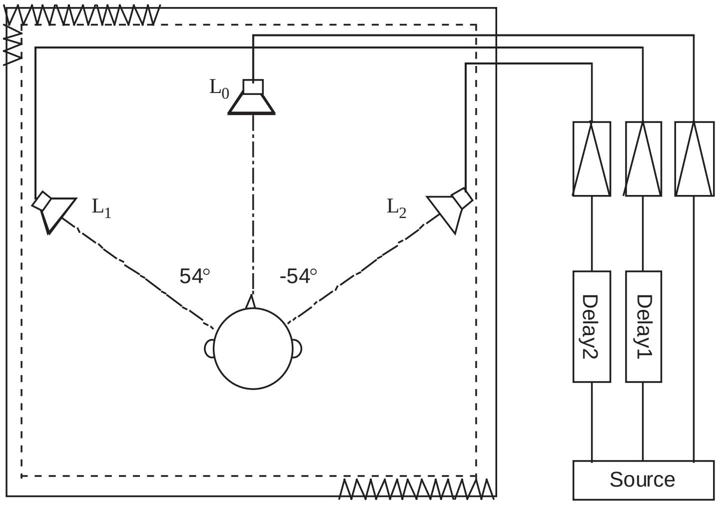

Fig. 2. Diagram of the sound simulation system used in experiments.

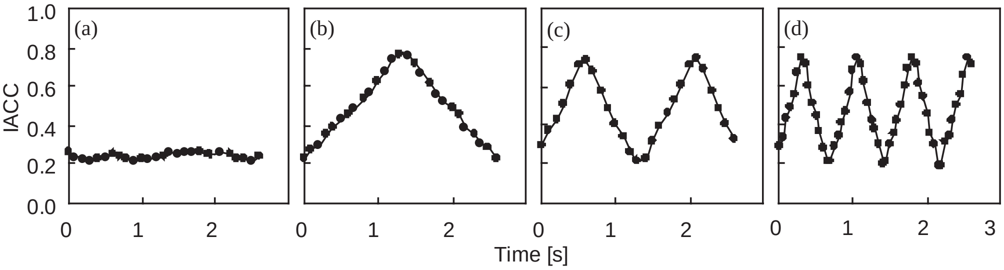

Fig. 3. Measured IACC for the experiment 1. (a) $E_p = \infty$ (integration interval for IACF, $2T = 0.3\,\mathrm{s}$; Flu_IACC $= 0.17\alpha_1$); (b) $E_p = 1.50$ ($2T = 0.3\,\mathrm{s}$; Flu_IACC $= 0.73\alpha_1$); (c) $E_p = 0.75$ ($2T = 0.25\,\mathrm{s}$; Flu_IACC $= 1.33\alpha_1$); (d) $E_p = 0.375$ ($2T = 0.1\,\mathrm{s}$; Flu_IACC $= 2.96\alpha_1$).

produce incoherent conditions, the time delays between the direct sound and the two reflections were set at $\Delta t_1 = 20\,\mathrm{ms}$ and $\Delta t_2 = 40\,\mathrm{ms}$. To simulate the fluctuation of IACC fixing the total SPL, the envelopes of the amplitude of the sounds of frontal and two reflections were modulated alternatively. The modulation period M_p, which is defined by the intervals between the times at maxima and minima of IACC, was set at 0.375, 0.75, 1.5 s, or ∞. The SPL were set at 65, 70, and 75 dBA (corresponding measured SPLs: 64.3–65.7, 69.2–70.7, and 74.1–75.7 dBA, respectively).

The measured values of running IACC are shown in Fig. 3. To measure tracing of the fluctuation of the IACC, the IACF was analyzed for the integration intervals $2T = 0.1$, 0.25, 0.3, and 0.3 s for the stimuli of M_p of 0.375, 0.75, 1.5 s, and ∞, respectively. The running interval was 0.1 s. On the other hand, in order to trace the loudness, $2T$, for analyzing the SPL, was set at the constant at 0.1 s for all stimuli, because the $(\tau_e)_{\min}$ of the stimuli was 3 ms ($2T$ is given by about $30(\tau_e)_{\min}$ [11]).

For more quantification of the fluctuation of IACC, Flu_IACC was obtained as follows: In general, the subjective scale value for IACC can be expressed by a nonlinear equation and can be formulated in terms of the $\frac{3}{2}$ power of the IACC [6]

$$S_{\mathrm{IACC}} \approx -\alpha_1 \mathrm{IACC}^{3/2}. \tag{4}$$

Let $S_{\mathrm{IACC}}(t)$ be the subjective effects of the IACC as a function of the time, then the derivative of $S_{\mathrm{IACC}}(t)$ is given by

$$\frac{\partial S_{\mathrm{IACC}}(t)}{\partial t} = \lim_{h \to 0} \frac{|S_{\mathrm{IACC}}(t) - S_{\mathrm{IACC}}(t-h)|}{h}. \tag{5}$$

The most subjectively effective piece of sound signal on annoyance, which is related to the IACC, may be obtained by $(\partial S_{\mathrm{IACC}}(t)/\partial t)_{\max}$. Thus, such a sampled data piece with constant time interval Δ is given by

$$\mathrm{Flu\_IACC} = \left(\frac{\partial S_{\mathrm{IACC}}(i\Delta)}{\partial i\Delta}\right)_{\max} = \frac{|S_{\mathrm{IACC}}(i\Delta) - S_{\mathrm{IACC}}((i-1)\Delta)|_{\max}}{\Delta}. \tag{6}$$

In our experimental conditions, $\Delta = 0.1\,\mathrm{s}$ is small enough to obtain a convergent value of the Flu_IACC. The values of Flu_IACC for the stimuli of $M_p = 0.375$, 0.75, 1.5 s, and ∞ were 2.34, 1.21, 0.72 and 0.17, respectively. Fluctuations in other spatial factors, W_{IACC} was within $-0.01 \pm 0.01\,\mathrm{ms}$, and τ_{IACC} was always within $\pm 0.02\,\mathrm{ms}$. Hence, listeners always perceived the frontal sound image in the median plane.

The paired-comparison tests were conducted for 12 stimuli (Four levels of Flu_IACC and three levels of SPL). Five subjects (four males and one female; 22–24 years old) with normal hearing ability participated. The subject was seated in a soundproof chamber and asked to judge which of two stimuli was perceived as more annoying. The duration of the stimuli was 3 s, the rise and fall times were 50 ms, and the silent interval between the stimuli was 1 s. Each pair of stimuli was presented in a random order separated by an interval of 3 s, which was the allotted time for the subject to respond. A single-test session consisted of 66 pairs ($N(N-1)/2$, $N = 12$) of stimuli. Ten sessions were performed for each subject. A single-test session was divided into two parts, each of which lasted 5.5 min, to prevent subject fatigue effects.

3.2. Results

Fifty responses (five subjects and 10 sessions) to each stimulus were obtained. Consistency tests indicated that all subjects had a significant ($p < 0.05$) ability to distinguish various degrees of annoyance. The test of agreement also indicated that there is significant ($p < 0.05$) agreement among all subjects. A scale value of annoyance was obtained by applying the law of comparative judgment (Thurstone's case V) and confirmed by the goodness of fit [12,13].

As shown in Fig. 4, the scale values of annoyance increased by increasing Flu_IACC and SPL as well. The moving sound images (Flu_IACC > 0) were always more annoying than the fixed sound image (Flu_IACC ≈ 0) when the SPL was constant. As shown in Table 1, the results of an analysis of variance for scale values of annoyance indicate that the factors Flu_IACC and SPL are significant ($p < 0.001$). The effects of the interaction between Flu_IACC and SPL were not significant. Thus, Flu_IACC and SPL contributed to the scale value of annoyance independently,

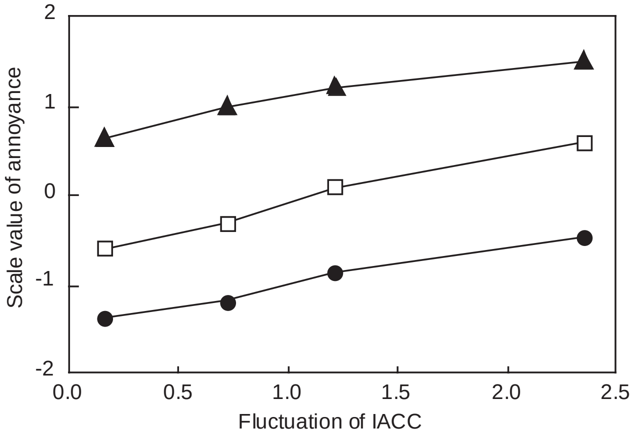

Fig. 4. Average scale values of annoyance as a function of Flu_IACC and as a parameter of SPL. ●: SPL = 65 dBA; □: SPL = 70 dBA; and ▲: SPL = 75 dBA.

Table 1
Results of the two-way ANOVA for scale values of annoyance with the factors Flu_IACC and SPL

Factor	Sum of squares	DF	Mean square	*F*-ratio	*p* Value
Flu_IACC	50156.55	3	16718.85	195.94	<0.001
SPL	241594.05	2	120797.02	1415.72	<0.001
Residual	511.95	6	85.33		

Table 2
Contributions and coefficients for each individual in experiment 1

Subject	Contribution (%)			Correlation coefficient	
	Flu_IACC	SPL	Total	*a*	*b*
A	11.0	88.2	99.2	—	—
B	18.8	79.6	98.4	0.47	0.19
C	11.2	88.0	99.2	0.36	0.20
D	32.7	65.1	97.8	—	—
E	14.5	84.6	99.1	0.38	0.18
Global	17.1	82.6	99.7	0.46	0.20

so that the scale value of annoyance may be given by

$$\text{SV\_annoyance} \approx f(\text{Flu\_IACC}) + f(\text{SPL}) \approx a(\text{Flu\_IACC}) + b(\text{SPL}). \qquad (7)$$

The coefficients obtained by multiple regression are: $a \approx 0.46$ and $b \approx 0.20$, which result in the best correlation between the measured and calculated scale values, 0.995 ($p<0.01$).

The coefficients a and b in Eq. (7) for each individual were also figured out as listed in Table 2. Two out of five subjects indicated that the scale values did not satisfy the model's goodness of fit, because the probability of their judgments in the paired-comparison tests was beyond the linear range of the scale value ($0.05 < p < 0.95$) [14]. For this reason, coefficients in Eq. (7) for subjects A and D could not be obtained.

4. Experiment 2: annoyance in relation to both SPL and τ_{IACC}

4.1. Procedure

As similar procedure to Experiment 1, annoyance judgments were performed by the paired-comparison method while changing fluctuations of the τ_{IACC} and the SPL. The source signal was bandpass filtered noise with the center frequency of 500 Hz (bandwidth = 160 Hz). The horizontally swaying sound images were simulated by the two lateral symmetrical sounds (L_1 and L_2) in a soundproof chamber (Fig. 2). To produce the fluctuation of τ_{IACC} fixing the total SPL, the envelopes of the amplitude of the sounds were modulated so that a sound image was altered between left and right. The M_p was set at 0.375, 0.75, 1.5 s or ∞. The SPL values set at 65, 70, and 75 dBA (measured SPLs were 63.3–66.2, 68.1–71.2, and 73.2–76.1, respectively).

The measured values of τ_{IACC} are shown in Fig. 5. To allow the fluctuation of τ_{IACC}, the IACF was calculated for the integration intervals $2T = 0.1$, 0.25, 0.3, and 0.3 s for the stimuli of M_p of 0.375, 0.75, 1.5 s, and ∞, respectively. The running interval was 0.1 s. To quantify the fluctuation of τ_{IACC}, Flu_τ_{IACC} is defined as follows:

It is assumed that the scale value for τ_{IACC} is expressed by a linear equation.

$$S_{\tau_{\mathrm{IACC}}} \approx -\alpha_2 \tau_{\mathrm{IACC}}. \tag{8}$$

Similar to Eq. (5), we obtain

$$\frac{\partial S_{\tau_{\mathrm{IACC}}}(t)}{\partial t} = \lim_{h \to 0} \frac{|S_{\tau_{\mathrm{IACC}}}(t) - S_{\tau_{\mathrm{IACC}}}(t-h)|}{h}. \tag{9}$$

Let Flu_τ_{IACC} be defined as the maximum fluctuation of the subjective scale values related to the τ_{IACC}, $(\partial S\tau_{\mathrm{IACC}}(t)/\partial t)_{\max}$, which may affect annoyance. Here, the fluctuation of the subjective

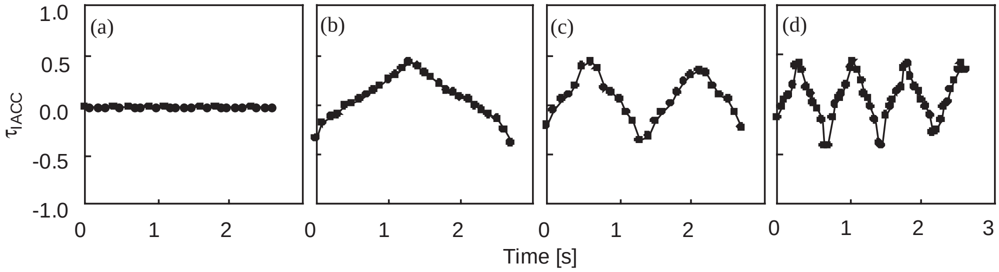

Fig. 5. Measured τ_{IACC} for experiment 2. (a) $E_p = \infty$ ($2T = 0.3$ s, Flu_$\tau_{\mathrm{IACC}} = 0.07\alpha_2$); (b) $E_p = 1.50$ ($2T = 0.3$ s, Flu_$\tau_{\mathrm{IACC}} = 1.50\alpha_2$); (c) $E_p = 0.75$ ($2T = 0.25$, Flu_$\tau_{\mathrm{IACC}} = 2.07\alpha_2$); (d) $E_p = 0.375$ ($2T = 0.1$ s, Flu_$\tau_{\mathrm{IACC}} = 3.73\alpha_2$).

scale value for τ_{IACC} is given by the sampled data strings with constant time interval Δ, thus,

$$\text{Flu\_}\tau_{\text{IACC}} = \left(\frac{\partial S_{\tau_{\text{IACC}}}(i\Delta)}{\partial i\Delta}\right)_{\max} = \frac{|S_{\tau_{\text{IACC}}}(i\Delta) - S_{\tau_{\text{IACC}}}((i-1)\Delta)|_{\max}}{\Delta}. \tag{10}$$

Practically, $\Delta = 0.1\,\text{s}$ is small enough for the convergence of the Flu_τ_{IACC}. Flu_τ_{IACC} for the stimuli of E_p of 0.375, 0.75, 1.5 s, and ∞ were 3.73, 2.07, 1.50, and 0.07, respectively. Fluctuations of the measured IACC and W_{IACC} were within 0.91 ± 0.08 and 0.27 ± 0.01 ms, respectively.

Similar to Experiment 1, the paired-comparison tests were conducted for 12 stimuli (four levels of Flu_τ_{IACC} and three levels of SPL) with the same five subjects.

4.2. Results

Fifty responses (five subjects and ten sessions) to each stimulus were also obtained. Consistency tests indicated that all subjects had a significant ($p<0.05$) ability to distinguish various degrees of annoyance. The test also indicated that there is significant ($p<0.05$) agreement among all subjects.

Fig. 6 shows the scale values of annoyance increased as Flu_τ_{IACC} and SPL increased. When the SPL was constant, the moving sound images (Flu_$\tau_{\text{IACC}} > 0$) were always more annoying than the fixed sound image (Flu_$\tau_{\text{IACC}} \approx 0$). As shown in Table 3, the results of an analysis of variance for

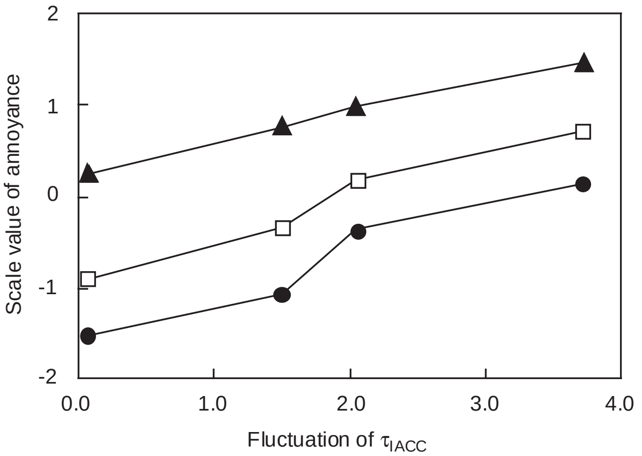

Fig. 6. Average scale values of annoyance as a function of Flu_τ_{IACC} and as a parameter of SPL. ●: SPL = 65 dBA; □: SPL = 70 dBA; and ▲: SPL = 75 dBA.

Table 3
Results of the two-way ANOVA for scale values of annoyance with the factors Flu_τ_{IACC} and SPL

Factor	Sum of squares	DF	Mean square	F-ratio	p Value
Flu_τ_{IACC}	104391.52	3	34797.17	494.18	<0.001
SPL	150706.18	2	75353.09	1010.14	<0.001
Residual	422.48	6	70.41		

Table 4
Contributions and coefficients for each individual in experiment 2

Subject	Contribution (%)			Correlation coefficient	
	Flu_τ_{IACC}	SPL	Total	a	b
A	40.2	59.3	99.5	0.37	0.14
B	25.5	71.2	96.7	0.31	0.17
C	15.6	83.5	99.1	0.24	0.19
D	79.2	19.6	98.8	0.50	0.08
E	46.7	51.6	98.3	—	—
Global	40.8	58.9	99.7	0.42	0.16

scale values of annoyance indicate that the factors Flu_τ_{IACC} and SPL are significant ($p<0.001$). The effects of the interaction between Flu_τ_{IACC} and SPL are not significant. Accordingly, Flu_τ_{IACC} and SPL contribute to the scale value of annoyance independently, so that

$$\mathrm{SV\_annoyance} \approx f(\mathrm{Flu\_}\tau_{\mathrm{IACC}}) + f(\mathrm{SPL}) \approx a(\mathrm{Flu\_}\tau_{\mathrm{IACC}}) + b(\mathrm{SPL}). \tag{11}$$

The coefficients obtained by multiple regression are $a \approx 0.42$ and $b \approx 0.16$. The calculated scale values agree well with measured ones with a correlation coefficient of 0.983 ($p<0.01$).

The coefficients a and b in Eq. (11) for each individual were also calculated (Table 4). One out of five subjects indicated that the scale values did not satisfy the model of goodness of fit. Therefore, the coefficients in Eq. (11) for subject E were not obtained. A comparison of the results from experiment 1, for all subjects, shows the effects of SPL are relatively small in the experimental conditions, so that effects of the Flu_τ_{IACC} cannot be ignored for the evaluation of annoyance.

5. Discussion

As listed in Tables 1 and 3, the contributions of the Flu_τ_{IACC} and the Flu_IACC to the scale value of annoyance are significant with the reference to the SPL difference of 10 dB. It is noteworthy that the variations in the ranges of SPL were from 65 to 75 dBA in both experiments.

Since the condition, $\tau_{\mathrm{IACC}} = 0$, is one of the preferred conditions for listening to sound [15], annoyance increased with the stimuli of Flu_$\tau_{\mathrm{IACC}} > 0$. In these experiments, the horizontal angles of lateral sounds were $\pm 54^\circ$, which is the most effective angle to obtain a low IACC for a sound source with the frequency range [6]. The value of IACC was alternated between 0.2 and 0.8 in experiment 1. However, the subjects found it hard to perceive a spatial fluctuation in respect to the IACC when it was lower than 0.4, because the just noticeable difference (JND) of IACC in the sound field with such a low IACC is larger than that with a higher IACC [16]. In order to avoid these kind of effects of nonlinearity, we introduced Eq. (4). Under these experimental conditions, 3.73 of the Flu_IACC is equivalent to an increase of 4.9 dB in the SPL, and 2.96 of the Flu_τ_{IACC} is equivalent to an increase of 9.7 dB in the SPL.

On the other hand, in experiment 2, the values of τ_{IACC} were changed from -0.4 to 0.4 ms and M_p was 0.375 s at minimum. The threshold of the interaural time delay (for the 1000 Hz tone) is 10 μs [17]. The M_p of 0.375 s is long enough to perceive the movement of the sound source [18,19]. In addition, all stimuli had clear sound images because the values of IACC for all stimuli in experiment 2 were greater than 0.82. Therefore, subjects equally perceived the fluctuation of τ_{IACC} during the whole period of the stimuli.

So far, it has been found that effects of the fluctuation in the spatial factors on annoyance are relatively large. A little is known about annoyance by the use of measured values of SPL and the spectrum analysis only. It is considered, for example, that the noise of a toilet flushing as mentioned in Section 1, which had a large fluctuation in the spatial factors, might have affected the residents.

6. Conclusions

The results of the study lead to the following conclusions:

1. Moving sound images were always more annoying than fixed sound images with a constant SPL.
2. The annoyance increased with increasing fluctuation of IACC as well as SPL.
3. The fluctuations of IACC and SPL independently contribute to the scale value of annoyance.
4. The annoyance increased with increasing fluctuation of τ_{IACC} as well as SPL.
5. The fluctuations of τ_{IACC} and SPL independently contribute to the scale value of annoyance.

For subjective evaluations of moving sound sources, it is recommended that binaural measurements be conducted to obtain the spatial factors extracted from the interaural cross-correlation function, in addition to the temporal factors extracted from the ACF.

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