# The influence of binaural effects on annoyance for transportation noise

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**A laboratory study was conducted to identify the significance of the binaural effect on annoyance by transportation noise. There were 377 participants (240 male and 137 female). Every participant marked the annoyance score (from 0 to 10) for each stimulus on their questionnaire. All of data were divided into four groups according to four types of transportation noise sources. The difference in the mean annoyance scores between subgroups according to sound recording/ playback techniques was statistically significant in the four noise groups. Stepwise multiple regression analysis was conducted. Using a regression model, predictions of $L_{Aeq}$, Technique and their interaction term ($L_{Aeq}$*Technique) involving dummy variable were made. In spite of some limitations of the process of the laboratory test, meaningful results were acquired. This study showed that the binaural effect was one of the acoustical factors modifying annoyance, and quantitative expression of binaural effect is suggested. Annoyance was explained by $L_{Aeq}$ and an interaction term in the resultant model functions for the four noise sources. Regression coefficients of the interaction term for each model equation were almost the same, which explained the extent of the binaural effect. The binaural effect was defined as the difference of annoyance variations between two sub-groups when $L_{Aeq}$ varies by $\Delta L_{Aeq}$ from the specified noise level. The binaural effect was expressed as $0.01\Delta L_{Aeq}$ on the basis of a 0 to 10 annoyance scale.** **© *2007 Institute of Noise Control Engineering.***

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## 1 INTRODUCTION

Environmental noises, such as transportation noise, recreational noise, industrial noise and community noise are recognized as environmental pollutants. Therefore, many studies on noise assessment have been performed in many countries in the field[1–5] and in the laboratory.[6–12] Thanks to these dedicated efforts, it is known that not only acoustical but non-acoustical factors influence annoyance. In particular, laboratory studies continue to report acoustical and non-acoustical factors that influence annoyance by comparing annoyance responses in the different situations.

Rylander et al.[6] selected noise from heavy trucks as stimuli in a laboratory experiment. Heavy truck noise included background noise from road traffic caused by other vehicles in a normal traffic situation. Also, window attenuation was simulated by a filter that reduced noise by 5 dB per octave. Subjects were tested in two different conditions (different noise level with the same number of noise events and different number of noise events with the same noise level). The results were that the extent of annoyance increased with the increase in $L_{Aeq}$ when the number of noise events was equal. At the same $L_{Aeq}$, the increase in the number of noise events caused an increase in annoyance.[6] Rasmussen[7] reported a relation between the number of events and subjective value caused by three noise sources and mixed stimuli. Relations between annoyance and noise metrics such as continuous equivalent sound pressure level ($L_{eq}$), noise pollution level ($LNP$) and three measures based on time-derivative, were compared.[7] According to Rasmussen, three measures based on time-derivative may be interpreted as $L_{eq}$ plus

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*Table 1—Acoustical characteristics and noise level of 15 noise events in test set 1.*

| No. of test set | No. | Noise source | Measurement device | $L_{Aeq}$ (dB) |
|---|---|---|---|---|
| 1 | 1 | Air(commercial) | Conventional microphone | 65 |
| | 2 | Road traffic | Dummy head | 80 |
| | 3 | Air(military) | Conventional microphone | 40 |
| | 4 | Air(commercial) | Dummy head | 50 |
| | 5 | Road traffic | Conventional microphone | 55 |
| | 6 | Air(military) | Dummy head | 80 |
| | 7 | Railway vehicle | Conventional microphone | 85 |
| | 8 | Road traffic | Dummy head | 60 |
| | 9 | Air(commercial) | Dummy head | 80 |
| | 10 | Road traffic | Conventional microphone | 94 |
| | 11 | Air(military) | Conventional microphone | 75 |
| | 12 | Air(military) | Dummy head | 60 |
| | 13 | Railway vehicle | Conventional microphone | 70 |
| | 14 | Railway vehicle | Dummy head | 40 |
| | 15 | Road traffic | Dummy head | 65 |

a correction term which should correspond to the expected increase in annoyance when the sound pressure level fluctuates. Also, research on annoyance by difference noise sources with various frequency characteristics has been performed. The difference of annoyance response caused by different noise sources was shown.[8,10]

In most research on community noise annoyance and noise assessment, noise metrics as independent variables for explanation of annoyance response are calculated from single microphone signals. Human being's auditory organ is, however, physiologically a two channel input system and sound reception is affected by the pinna, head and body as sound enters each ear channel.[13] The external ears distort the original sounds and the extent of distortion is represented by the external ear transfer functions (usually called Head Related Transfer Functions (HRTFs), which depends on the distance and direction from source related to the head).[13] The external ear is composed of pinna, head and torso. The acoustical effects of the pinna are based on reflection, diffraction, shadowing and dispersion.[13] Dominant acoustical effects around the head vary according to wave length (compared with head dimen-

*Table 2—Acoustical characteristics and noise level of 14 noise events in test set 2.*

| No. of test set | No. | Noise source | Measurement device | $L_{Aeq}$ (dB) |
|---|---|---|---|---|
| 2 | 1 | Air(military) | Conventional microphone | 70 |
| | 2 | Road traffic | Conventional microphone | 40 |
| | 3 | Air(commercial) | Dummy head | 75 |
| | 4 | Air(military) | Dummy head | 55 |
| | 5 | Railway vehicle | Conventional microphone | 45 |
| | 6 | Railway vehicle | Dummy head | 60 |
| | 7 | Air(military) | Conventional microphone | 85 |
| | 8 | Air(commercial) | Dummy head | 90 |
| | 9 | Air(military) | Conventional microphone | 90 |
| | 10 | Road traffic | Dummy head | 85 |
| | 11 | Railway vehicle | Conventional microphone | 75 |
| | 12 | Air(military) | Conventional microphone | 45 |
| | 13 | Air(commercial) | Dummy head | 55 |
| | 14 | Railway vehicle | Dummy head | 65 |

*Table 3—Acoustical characteristics and noise level of 15 noise events in test set 3.*

| No. of test set | No. | Noise source | Measurement device | $L_{Aeq}$ (dB) |
|---|---|---|---|---|
| 3 | 1 | Road traffic | Conventional microphone | 70 |
| | 2 | Air(commercial) | Dummy head | 70 |
| | 3 | Railway vehicle | Conventional microphone | 55 |
| | 4 | Air(military) | Dummy head | 50 |
| | 5 | Air(commercial) | Conventional microphone | 45 |
| | 6 | Road traffic | Dummy head | 90 |
| | 7 | Air(commercial) | Conventional microphone | 85 |
| | 8 | Air(commercial) | Dummy head | 60 |
| | 9 | Railway vehicle | Dummy head | 80 |
| | 10 | Railway vehicle | Conventional microphone | 88 |
| | 11 | Road traffic | Conventional microphone | 75 |
| | 12 | Road traffic | Dummy head | 50 |
| | 13 | Railway vehicle | Conventional microphone | 50 |
| | 14 | Air(commercial) | Dummy head | 40 |
| | 15 | Air(military) | Dummy head | 65 |

sion). Because of these acoustical effects around head and pinna, the ears play an important role of spatial hearing.[13] Because of the HRTFs, noise received by a dummy head has different frequency and level characteristics relative to the same signal received by a single microphone. This means that sounds used in calculating noise metrics are different from sounds heard by subjects. But, no comment on this fact is included in the above-mentioned papers. Through the headphone reproduction of the single microphone signals and HATS (Head And Torso Simulator, Brüel & Kjær Type 4100) signal, subjective responses to the signals recorded by a single microphone and the binaural signal recorded by a dummy head are compared in this paper. There were some limitations to this laboratory study. Each listener's head is unique. Each individual HRTF is slightly different from HRTF of HATS. When subjects listen to test sounds, headphone corrections (including a correction for sound field between headphone and subjects' ears) for individual ears are slightly different from that in the artificial ears of HATS. But, most dummy heads have been designed using an averaging technique so that their HRTFs are the average of individual HRTFs.[13] These effects are less important than the fact that tonal auditory signals are distorted by the HRTFs.[13] In this paper, it will be proposed and demonstrated by laboratory study that the

*Table 4—Acoustical characteristics and noise level of 14 noise events in test set 4.*

| No. of test set | No. | Noise source | Measurement device | $L_{Aeq}$ (dB) |
|---|---|---|---|---|
| 4 | 1 | Railway vehicle | Conventional microphone | 65 |
| | 2 | Air(commercial) | Conventional microphone | 55 |
| | 3 | Air(military) | Dummy head | 45 |
| | 4 | Railway vehicle | Dummy head | 75 |
| | 5 | Road traffic | Conventional microphone | 85 |
| | 6 | Air(military) | Dummy head | 90 |
| | 7 | Air(commercial) | Conventional microphone | 90 |
| | 8 | Air(military) | Dummy head | 85 |
| | 9 | Railway vehicle | Conventional microphone | 60 |
| | 10 | Railway vehicle | Dummy head | 45 |
| | 11 | Air(military) | Conventional microphone | 55 |
| | 12 | Air(commercial) | Conventional microphone | 75 |
| | 13 | Road traffic | Dummy head | 40 |
| | 14 | Air(military) | Dummy head | 70 |

*Table 5—Acoustical characteristics and noise level of 15 noise events in test set 5.*

| No. of test set | No. | Noise source | Measurement device | $L_{Aeq}$ (dB) |
|---|---|---|---|---|
| 5 | 1 | Air(military) | Conventional microphone | 65 |
| | 2 | Air(commercial) | Conventional microphone | 40 |
| | 3 | Railway vehicle | Dummy head | 50 |
| | 4 | Road traffic | Conventional microphone | 50 |
| | 5 | Road traffic | Dummy head | 75 |
| | 6 | Railway vehicle | Dummy head | 88 |
| | 7 | Railway vehicle | Conventional microphone | 80 |
| | 8 | Air(commercial) | Conventional microphone | 60 |
| | 9 | Air(commercial) | Dummy head | 85 |
| | 10 | Road traffic | Conventional microphone | 90 |
| | 11 | Air(commercial) | Dummy head | 45 |
| | 12 | Air(military) | Conventional microphone | 50 |
| | 13 | Railway vehicle | Dummy head | 55 |
| | 14 | Air(commercial) | Conventional microphone | 70 |
| | 15 | Road traffic | Dummy head | 70 |

binaural effect is one of the acoustic factors that have an effect on annoyance.

## 2 MEASUREMENT AND STIMULUS

### 2.1 Measurement

In order to investigate the binaural effects on noise annoyance, transportation noise was recorded by single microphone (Brüel & Kjær 4190) and by HATS (Head And Torso Simulator, Brüel & Kjær Type 4100) simultaneously. Both measurement devices were placed about 15 m away from the edge of road and railway, and about 100 m away from takeoff and landing point of military and commercial aircraft at a 1.7 m height above the ground. The single microphone was located about 5 m away from the dummy head along a line parallel to the track of noise sources. It is impossible for two measurement devices to be located at the same position simultaneously and it is unavoidable that dummy head obstructs the sound. However, noises reaching the two measurement devices are almost same because measurements were performed in open environment with no obstacles at nearly equal distance from the source. Also, the extent of acoustical interference of the signal measured by the microphone

*Table 6—Acoustical characteristics and noise level of 15 noise events in test set 6.*

| No. of test set | No. | Noise source | Measurement device | $L_{Aeq}$ (dB) |
|---|---|---|---|---|
| 6 | 1 | Road traffic | Conventional microphone | 65 |
| | 2 | Railway vehicle | Conventional microphone | 40 |
| | 3 | Railway vehicle | Dummy head | 70 |
| | 4 | Air(military) | Conventional microphone | 60 |
| | 5 | Air(military) | Dummy head | 75 |
| | 6 | Road traffic | Dummy head | 94 |
| | 7 | Air(commercial) | Conventional microphone | 80 |
| | 8 | Road traffic | Conventional microphone | 60 |
| | 9 | Railway vehicle | Dummy head | 85 |
| | 10 | Air(military) | Conventional microphone | 80 |
| | 11 | Road traffic | Dummy head | 55 |
| | 12 | Air(commercial) | Conventional microphone | 50 |
| | 13 | Air(military) | Dummy head | 40 |
| | 14 | Road traffic | Conventional microphone | 80 |
| | 15 | Air(commercial) | Dummy head | 65 |

*Table 7—Number of participants according sex in each test set.*

| No. of test set | Set 1 | Set 2 | Set 3 | Set 4 | Set 5 | Set 6 |
|---|---|---|---|---|---|---|
| Male | 39 | 37 | 32 | 36 | 47 | 49 |
| Female | 20 | 22 | 26 | 26 | 21 | 22 |
| Total | 59 | 59 | 58 | 62 | 68 | 71 |

produced by the dummy head was negligible, because the dummy head was placed about 5 m away from the microphone.

The two measurement devices were directly connected to a PULSE (Brüel & Kjær 3560C) for sound recording, real-time monitoring and spectral analysis. Each recorded sound from commercial aircraft, military aircraft and railway was a single noise event, which was generated from one passby. Recorded road traffic noise represented by general highway traffic contained a number of vehicles (heavy and light vehicles) whose velocity ranged from 80 to 120 km/h. Sampling rate was set to 65536 Hz with 16 bit quantization.

## 2.2 Constitution of Stimuli

Using Cool edit pro *ver.* 2.0 software, military and commercial aircraft noises were generated with the increment of $L_{Aeq}$ (equivalent continuous A-weighted sound pressure level) of 5 dBA from $L_{Aeq}$=40 to 90 dBA. Railway and road traffic noise events were generated for 40, 45, 50, 55, 60, 65, 70, 75, 80, 85 and 88 dBA and 40, 50, 55, 60, 65, 70, 75, 80, 85, 90 and 94 dBA, respectively. A total of 6 test sets were composed from 88 noise events. 44 noise events were generated from the sounds that had been recorded by the single microphone and the others were generated from the sounds that had been recorded by the dummy head. 88 noise events were randomly arranged in each test set. The constitution of each test set is summarized in Tables 1–6. The duration of the recordings of the aircraft noise, railway noise and road traffic noise events were about 15 sec. Silence between noise events in six test sets lasted about 10 sec.

# 3 LABORATORY EXPERIMENT

## 3.1 Subjects

Total 380 persons participated in laboratory study. One person's data was lost and two of the 380 persons did not have normal hearing (i.e. hearing loss greater the 20 dB of RETSPL[14]). All of subjects were paid fees for participation. Available data was acquired from tests conducted with 377 subjects (240 men and 137

*Table 8—Relation between equivalent noise level and annoyance from commercial aircraft noise according to participants' sex.*

| $L_{Aeq}$ (dBA) | Measurement device | Annoyance (mean ± standard deviation) | | |
|---|---|---|---|---|
| | | male | female | average |
| 40 | Conventional microphone | 2.36±1.67 | 1.62±1.77 | 2.13±1.73 |
| 45 | Conventional microphone | 2.81±1.75 | 3.27±2.31 | 3.02±2.01 |
| 50 | Conventional microphone | 2.78±1.79 | 2.73±1.55 | 2.76±1.71 |
| 55 | Conventional microphone | 4.14±1.97 | 3.69±4.14 | 3.95±1.97 |
| 60 | Conventional microphone | 4.06±1.72 | 4.14±2.03 | 4.09±1.81 |
| 65 | Conventional microphone | 4.15±2.40 | 3.50±1.99 | 3.93±2.27 |
| 70 | Conventional microphone | 5.94±1.89 | 6.19±1.17 | 6.01±1.70 |
| 75 | Conventional microphone | 6.47±2.14 | 6.81±1.96 | 6.61±2.06 |
| 80 | Conventional microphone | 7.20±2.15 | 7.27±1.58 | 7.23±1.98 |
| 85 | Conventional microphone | 8.56±1.68 | 8.42±1.68 | 8.50±1.67 |
| 90 | Conventional microphone | 8.97±1.63 | 9.08±1.57 | 9.02±1.59 |
| 40 | Dummy head | 2.91±2.13 | 3.00±2.04 | 2.91±2.13 |
| 45 | Dummy head | 3.04±1.61 | 2.81±1.89 | 3.04±1.61 |
| 50 | Dummy head | 4.18±2.43 | 3.15±2.16 | 4.18±2.43 |
| 55 | Dummy head | 4.30±2.20 | 4.05±2.03 | 4.30±2.20 |
| 60 | Dummy head | 4.91±1.94 | 4.81±2.08 | 4.91±1.94 |
| 65 | Dummy head | 5.69±2.27 | 6.18±1.82 | 5.69±2.27 |
| 70 | Dummy head | 6.75±1.98 | 6.38±2.26 | 6.75±1.98 |
| 75 | Dummy head | 7.92±2.31 | 7.91±2.18 | 7.92±2.31 |
| 80 | Dummy head | 8.33±2.34 | 8.30±1.87 | 8.33±2.34 |
| 85 | Dummy head | 9.04±1.23 | 9.43±0.87 | 9.04±1.23 |
| 90 | Dummy head | 9.76±0.64 | 9.32±1.62 | 9.76±0.64 |

*Table 9—Relation between equivalent noise level and annoyance from military aircraft noise according to participants' sex.*

| $L_{Aeq}$ (dBA) | Measurement device | Annoyance (mean ± standard deviation) | | |
|---|---|---|---|---|
| | | male | female | average |
| 40 | Conventional microphone | 1.79±1.59 | 2.35±1.95 | 1.98±1.73 |
| 45 | Conventional microphone | 2.27±1.63 | 2.14±1.78 | 2.22±1.67 |
| 50 | Conventional microphone | 3.02±1.66 | 2.48±1.86 | 2.85±1.73 |
| 55 | Conventional microphone | 3.33±1.66 | 3.58±2.47 | 3.44±2.02 |
| 60 | Conventional microphone | 4.49±1.67 | 3.59±2.22 | 4.21±1.89 |
| 65 | Conventional microphone | 4.72±1.78 | 3.81±1.57 | 4.44±1.76 |
| 70 | Conventional microphone | 5.84±1.80 | 4.77±2.02 | 5.44±1.94 |
| 75 | Conventional microphone | 5.54±2.19 | 5.45±1.39 | 5.51±1.94 |
| 80 | Conventional microphone | 6.69±2.15 | 6.95±1.99 | 6.77±2.09 |
| 85 | Conventional microphone | 8.92±1.42 | 8.14±1.91 | 8.63±1.65 |
| 90 | Conventional microphone | 8.76±1.64 | 8.00±2.00 | 8.47±1.80 |
| 40 | Dummy head | 2.06±1.59 | 2.09±1.87 | 2.07±1.67 |
| 45 | Dummy head | 3.25±2.32 | 2.58±1.79 | 2.97±2.13 |
| 50 | Dummy head | 3.50±1.81 | 3.77±2.12 | 3.62±1.95 |
| 55 | Dummy head | 4.19±1.93 | 3.82±2.22 | 4.05±2.03 |
| 60 | Dummy head | 4.03±1.99 | 3.90±1.62 | 3.98±1.86 |
| 65 | Dummy head | 5.97±2.16 | 6.15±2.41 | 6.05±2.26 |
| 70 | Dummy head | 6.25±2.14 | 6.73±2.16 | 6.45±2.15 |
| 75 | Dummy head | 7.22±2.09 | 6.91±1.66 | 7.13±1.96 |
| 80 | Dummy head | 7.79±2.26 | 8.55±1.99 | 8.05±2.18 |
| 85 | Dummy head | 8.33±1.76 | 8.54±1.79 | 8.42±1.76 |
| 90 | Dummy head | 9.11±1.62 | 9.46±1.17 | 9.26±1.45 |

women). Their ages ranged from 20 to 61 years. All of subjects heard only one test set among six test sets in an anechoic chamber after taking an audiometric screening test. They marked the extent of annoyance from each noise event on a questionnaire.

## 3.2 Apparatus

In order to test subjective response to transportation noise, a system which could control the sound in an anechoic chamber through a desk top PC (Pentium IV) with DIGI 96 Pro sound card (RME) was constructed. Only the subject and headphone (Sennheiser HD25) were located in the anechoic chamber. In addition, sound monitoring system was connected to a PULSE (Brüel & Kjær Type 3560C) to calibrate the sound pressure level and spectrum level before each laboratory test.

Frequency characteristics of the single microphone as well as microphones mounted in the ears of the dummy head, which were used to record transportation noise events, were flat in the frequency range from 20 Hz to 20 kHz. So, it could be said that there was no distortion of the recorded sounds. However, frequency response of headphone and sound field between headphone and subjects' ears could distort the original sounds. In order to compensate for the sound distortion caused by these two problems, white noise was heard by both ears of the dummy head through a headphone. Output terminal of the dummy head was directly connected to the PULSE, which contained a frequency analyzer and 1/3 octave band analyzer. The input signal to the dummy head ears (output sound for calibration) was analyzed in frequency domain. The inversion of the frequency response functions for the headphone and diffuse field (sound field between headphone and subjects' ears) provided correction factors which compensated for levels to which the subjects were exposed from recordings from the single microphone and the dummy head.

After the calibration of level and spectrum had been completed, the laboratory experiment was conducted in the anechoic chamber in order to avoid interference from other noises. The size of test section was 3.2 × 3.2 × 2.1 m and cut off frequency was approximately 200 Hz. Background noise levels in an anechoic chamber were about 20 ~ 23 dBA.

## 3.3 Procedures

All of the people who participated in laboratory test were audiometrically screened before the main test. If

*Table 10—Relation between equivalent noise level and annoyance from railway noise according to participants' sex.*

| $L_{Aeq}$ (dBA) | Measurement device | Annoyance (mean ± standard deviation) | | |
|---|---|---|---|---|
| | | male | female | average |
| 40 | Conventional microphone | 2.02±1.55 | 1.55±1.18 | 2.02±1.55 |
| 45 | Conventional microphone | 2.73±1.79 | 2.45±1.95 | 2.73±1.79 |
| 50 | Conventional microphone | 2.56±1.61 | 3.00±1.81 | 2.56±1.61 |
| 55 | Conventional microphone | 2.91±1.67 | 3.58±2.21 | 2.91±1.67 |
| 60 | Conventional microphone | 3.50±2.01 | 3.69±2.54 | 3.50±2.01 |
| 65 | Conventional microphone | 4.25±2.45 | 4.04±1.91 | 4.25±2.45 |
| 70 | Conventional microphone | 5.49±2.19 | 5.20±1.99 | 5.49±2.19 |
| 75 | Conventional microphone | 6.16±1.91 | 5.27±2.29 | 6.16±1.91 |
| 80 | Conventional microphone | 7.77±1.54 | 7.43±1.83 | 7.77±1.54 |
| 85 | Conventional microphone | 8.74±1.67 | 8.10±2.63 | 8.74±1.67 |
| 88 | Conventional microphone | 8.56±1.63 | 8.46±2.08 | 8.56±1.63 |
| 40 | Dummy head | 1.82±1.78 | 1.50±1.43 | 1.71±1.66 |
| 45 | Dummy head | 2.19±1.47 | 2.54±1.86 | 2.34±1.64 |
| 50 | Dummy head | 3.72±1.80 | 2.86±2.03 | 3.46±1.90 |
| 55 | Dummy head | 4.04±1.99 | 3.71±1.82 | 3.94±1.93 |
| 60 | Dummy head | 5.03±1.98 | 4.77±2.33 | 4.93±2.10 |
| 65 | Dummy head | 5.62±2.11 | 5.00±1.80 | 5.39±2.01 |
| 70 | Dummy head | 6.02±1.80 | 5.68±1.78 | 5.92±1.79 |
| 75 | Dummy head | 7.39±2.11 | 7.69±2.00 | 7.52±2.05 |
| 80 | Dummy head | 7.91±1.67 | 8.08±2.19 | 7.98±1.91 |
| 85 | Dummy head | 8.57±1.95 | 8.73±1.28 | 8.62±1.76 |
| 88 | Dummy head | 9.17±1.58 | 9.43±1.21 | 9.25±1.47 |

subjects had hearing losses less than 20 dB of RETSPL,[14] they were regarded as normal. After audiometric screening test, subjects were instructed on the procedure and the method of experiment. The main contents of the instructions were as follows.

(1) Whatever makes a noise or disturbs an experiment should be ignored from subjects

(2) Annoyance is different from level and loudness of noise events. Thus, level and loudness itself of each noise event must not be compared.

(3) Subjects may imagine reading a book, watching TV or a similar activity.

(4) Marking an annoyance score on the questionnaire should be performed when no sound is heard after hearing each noise event. Enough time to mark the annoyance score is given.

After instructions were given to the subjects, laboratory experiments followed. All of the subjects performed one test set among the 6 test sets. Subjects were exposed to both transportation noise recorded by the single microphone and by the dummy head in one test set. They then recorded the extent of annoyance in the questionnaire. Subjects were asked to answer the question, "What extent of annoyance do you feel as if you heard the noise in your common environment?" There exists various annoyance scales such as 5- or 7- or 9-point verbal and numerical scale. However, annoyance rating scale adopted in this experiment was an 11-point numerical scale, ranging from zero to ten. Ten means "extremely annoyed" and zero means "not annoyed at all." The choice of the 11-point numerical scale is based on the assumption that respondents are more cognitively familiar with 0-10 scaling than with the shorter 7 or 9-point numeric scales.[15]

### 3.4 Status of Laboratory Test

The number of subjects for each test set is summarized in Table 7. 59 subjects performed test set 1 and 2. 58, 62, 68 and 71 subjects performed test set 3, 4, 5 and 6, respectively. Thus, 5534 points were collected in the database.

## 4 ANALYSIS AND RESULT

Tables 8–11 show the relation between annoyance and equivalent noise level from commercial aircraft, military aircraft noise, railway noise and road traffic noise. It was found from Tables 8–11 that the relation between noise levels and their corresponding annoyance score was almost linear. Also, the mean annoyance score from noise recorded by the dummy head

*Table 11—Relation between equivalent noise level and annoyance from road noise according to participants' sex.*

| $L_{Aeq}$ (dBA) | Measurement device | Annoyance (mean ± standard deviation) | | |
|---|---|---|---|---|
| | | male | female | average |
| 40 | Conventional microphone | 1.27±1.04 | 1.68±1.81 | 1.42±1.38 |
| 50 | Conventional microphone | 2.47±1.52 | 1.71±1.45 | 2.24±1.53 |
| 55 | Conventional microphone | 2.77±2.07 | 2.75±2.24 | 2.76±2.11 |
| 60 | Conventional microphone | 2.76±1.61 | 2.50±1.47 | 2.68±1.57 |
| 65 | Conventional microphone | 3.53±1.92 | 2.82±2.08 | 3.31±1.98 |
| 70 | Conventional microphone | 4.50±1.65 | 4.38±1.75 | 4.45±1.68 |
| 75 | Conventional microphone | 5.03±1.73 | 4.96±2.55 | 5.00±2.12 |
| 80 | Conventional microphone | 6.94±1.80 | 6.95±1.84 | 6.94±1.80 |
| 85 | Conventional microphone | 7.75±2.14 | 8.19±1.83 | 7.94±2.02 |
| 90 | Conventional microphone | 7.98±1.79 | 7.52±2.04 | 7.84±1.87 |
| 94 | Conventional microphone | 8.95±1.41 | 8.20±2.44 | 8.69±1.84 |
| 40 | Dummy head | 1.78±1.42 | 1.69±1.89 | 1.74±1.62 |
| 50 | Dummy head | 2.28±1.75 | 2.19±1.72 | 2.24±1.72 |
| 55 | Dummy head | 2.24±1.51 | 1.86±1.25 | 2.13±1.43 |
| 60 | Dummy head | 3.41±2.10 | 2.85±1.79 | 3.22±2.00 |
| 65 | Dummy head | 4.92±2.31 | 4.15±1.95 | 4.66±2.21 |
| 70 | Dummy head | 6.06±1.76 | 6.14±1.31 | 6.09±1.63 |
| 75 | Dummy head | 7.26±1.69 | 7.10±1.64 | 7.21±1.66 |
| 80 | Dummy head | 7.18±2.32 | 7.55±2.42 | 7.31±2.34 |
| 85 | Dummy head | 8.51±1.54 | 7.09±2.43 | 7.98±2.02 |
| 90 | Dummy head | 9.00±2.02 | 9.15±1.43 | 9.07±1.77 |
| 94 | Dummy head | 9.22±1.65 | 9.50±1.01 | 9.31±1.48 |

*Table 12—Summery of the result of one-way ANOVA in commercial aircraft noise group.*

| | Sum of squares | Degrees of freedom | Mean square | F | Significance |
|---|---|---|---|---|---|
| Between groups | 252.871 | 1 | 25.871 | 28.409 | <0.0001 |
| Within groups | 122292.205 | 1381 | 8.901 | | |
| Total | 12545.076 | 1382 | | | |

F(1, ∞, 0.95)=3.84; F(1, ∞, 0.99)=6.63

*Table 13—Robust tests of equality of means in millitary aircraft noise group.*

| | Statistic | Degrees of freedom 1 | Degrees of freedom 2 | Significance |
|---|---|---|---|---|
| Welch | 21.731 | 1 | 1365.393 | <0.0001 |
| Brown-Forsythe | 21.731 | 1 | 1365.393 | <0.0001 |

*Table 14—Summery of the results of one-way ANOVA in railway noise group.*

| | Sum of squares | Degrees of freedom | Mean square | F | Significance |
|---|---|---|---|---|---|
| Between groups | 171.375 | 1 | 171.375 | 18.640 | <0.0001 |
| Within groups | 12650.710 | 1376 | 9.194 | | |
| Total | 12822.084 | 1377 | | | |

$F(1,\infty,0.95)=3.84$; $F(1,\infty,0.99)=6.63$

was slightly higher than that by the single microphone. In order to identify the statistical significance of binaural effects on annoyance more precisely, all data were divided into four groups according to the four noise sources. Statistical analysis (one-way ANOVA and regression analysis) was conducted for the four groups.

As is well known, ANOVA is a method to compare means between two or more groups. In this research, means of two categories (or sub-groups) classified by sound recording/playback technique were compared in four groups. Homogeneous variance assumption should be met for which the result of ANOVA was reliable. Preliminary test, which is Levene's test, for homogeneity of variance, was carried out in each noise source group. Variances in the two categories (according to sound recording/playback technique) were equal ($P > 0.05$) in the cases of commercial aircraft noise and railway noise but were not in the other cases ($P < 0.05$). If the equal variances assumption has been violated, the Welch or Brown-Forsythe statistic instead of the usual $F$-statistic was used to test for the difference of means between groups.[16]. Tables 12 and 14 show the results of ANOVA for the commercial aircraft noise and the railway noise group. Tables 13 and 15 show the results of robust tests for equality of means for the military aircraft noise group and the road traffic noise group. As shown in Tables 12–15, the significance of $F$ statistic and Welch statistic (or Brown-Forsythe statistic) was less than 0.01. Therefore null hypothesis (meaning that the two groups are equal) was rejected in all cases. It was statistically significant that binaural effects influenced the annoyance ($p < 0.01$).

Stepwise multiple regression analysis was conducted in each group in order to examine more precisely that binaural effect was an effective modifier. The annoyance score was the response variable. Let A-weighted equivalent level, dummy variable (sound recording/playback technique) and their interaction term ($L_{Aeq}$* *Technique*) involving the dummy variable be predictors in order that the interaction effect as well as main effect could be considered. Sound recording/playback technique as predictor will be simply referred to as the technique from henceforth. Properties of the dummy variable and interaction term ($L_{Aeq}$* *Technique*) are shown below.

$$\begin{aligned} \mathit{Technique} &= 0 \quad \textit{in case of the microphone recording} \\ &= 1 \quad \textit{in case of the dummy head recording} \end{aligned} \tag{1}$$

$$\begin{aligned} \mathit{Interaction\ Term} &= 0 \quad \textit{in case of the microphone recording} \\ &= LAeq \quad \textit{in case of the dummy head recording} \end{aligned} \tag{2}$$

The basic procedure of stepwise regression analysis is as follows. Firstly, the independent variable best correlated with the dependent variable is included in the regression equation. The significance of the

*Table 15—Robust tests of equality of means in road traffic noise group.*

| | Statistic | Degrees of freedom 1 | Degrees of freedom 2 | Significance |
|---|---|---|---|---|
| Welch | 18.229 | 1 | 1384.106 | <0.001 |
| Brown-Forsythe | 18.229 | 1 | 1384.106 | <0.001 |

included independent variable is checked. If it is not significant, regression analysis is stopped and regression model is determined to be the mean value of response variable. Otherwise, the independent variable with the highest partial $F$ with the dependent variable among the remaining independent variables is entered. This process was repeated until the addition of a remaining independent variable did not increase R-squared by a significant amount (significance level used in this research is 0.05).[17]

The result of stepwise regression analysis is summarized in Table 16. In this table, group A, B, C and D means the commercial aircraft noise, military aircraft noise, railway noise and road traffic noise, respectively. It was found that regression coefficients were statistically significant ($p < 0.01$) and the entry of the interaction term ($L_{Aeq} * Technique$) caused a significant increase in the R-square value in Table 16. In all groups, predictors of the resultant model equations were A-weighted equivalent level and interaction term ($L_{Aeq} * Technique$) so that the mathematical expression of resultant regression model was as below.

$$\hat{Y}(annoyance) = b_0 + b_1 L_{Aeq} + b_2 L_{Aeq} * Technique \tag{3}$$

$$\hat{Y}(annoyance) \begin{array}{ll} = b_0 + b_1 L_{Aeq} & for\ Technique = 0 \\ = b_0 + (b_1 + b_2) L_{Aeq} & for\ Technique = 1 \end{array} \tag{4}$$

*Table 16—Summery of the results of regression analysis in each group (regression models and coefficients$^c$).*

| Group | | Model | Unstandardized coefficients | | Standardized coefficients | t | Significance | R | R Square | Adjusted R Square |
|---|---|---|---|---|---|---|---|---|---|---|
| | | B | Std. error | Beta | | | | | | |
| A | 1 | (Intercept) | −3.734 | .226 | | −16.515 | <0.0001 | | | |
| | | $L_{Aeq}$ | .144 | .003 | .752 | 42.427 | <0.0001 | .752$^a$ | .566 | .566 |
| | 2 | (Intercept) | −3.721 | .221 | | −16.814 | <0.0001 | | | |
| | | $L_{Aeq}$ | .137 | .003 | .720 | 40.330 | <0.0001 | .765$^b$ | .585 | .584 |
| | | $L_{Aeq}$ × Technique | .012 | .002 | .140 | 7.869 | <0.0001 | | | |
| B | 1 | (Intercept) | −3.878 | .224 | | −17.327 | <0.0001 | | | |
| | | $L_{Aeq}$ | .141 | .003 | .750 | 41.989 | <0.0001 | .750$^a$ | .562 | .562 |
| | 2 | (Intercept) | −3.869 | .220 | | −17.610 | <0.0001 | | | |
| | | $L_{Aeq}$ | .135 | .003 | .719 | 39.897 | <0.0001 | .760$^b$ | .578 | .577 |
| | | $L_{Aeq}$ × Technique | .011 | .002 | .131 | 7.269 | <0.0001 | | | |
| C | 1 | (Intercept) | −4.540 | .223 | | −20.362 | <0.0001 | | | |
| | | $L_{Aeq}$ | .151 | .003 | .773 | 45.187 | <0.0001 | .773$^a$ | .597 | .597 |
| | 2 | (Intercept) | −4.519 | .220 | | −20.537 | <0.0001 | | | |
| | | $L_{Aeq}$ | .146 | .003 | .746 | 42.815 | <0.0001 | .780$^b$ | .608 | .608 |
| | | $L_{Aeq}$ × Technique | .010 | .002 | .108 | 6.200 | <0.0001 | | | |
| D | 1 | (Intercept) | −5.601 | .226 | | −24.764 | <0.0001 | | | |
| | | $L_{Aeq}$ | .155 | .003 | .796 | 49.027 | <0.0001 | .796$^a$ | .633 | .633 |
| | 2 | (Intercept) | −5.592 | .222 | | −25.186 | <0.0001 | | | |
| | | $L_{Aeq}$ | .150 | .003 | .768 | 46.980 | <0.0001 | 804$^b$ | .647 | .646 |
| | | $L_{Aeq}$ × Technique | .010 | .001 | .120 | 7.333 | <0.0001 | | | |

[a] Predictors: (Intercept), $L_{Aeq}$
[b] Predictors: (Intercept), $L_{Aeq}$, $L_{Aeq}$ × Technique
[c] Dependent variable: Annoyance

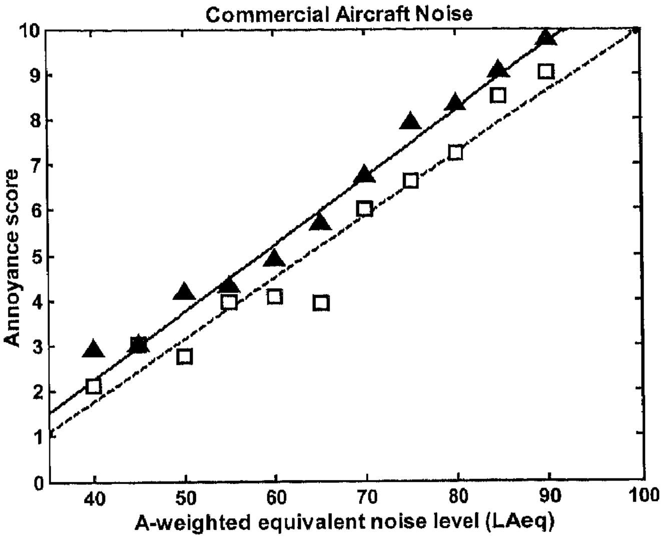

*Fig. 1—Comparison of subjective responses to commercial aircraft noise between two different sound recording/playback techniques (Real line and triangular symbol represents regression model and observed data when subjects were tested through sound recorded by a dummy head, respectively. Dotted line and rectangular symbol represents regression model and observed data when subjects were tested through sound recorded by a single microphone, respectively).*

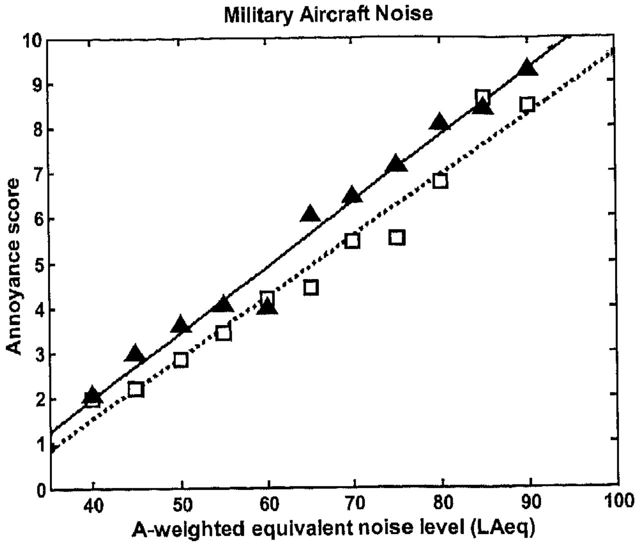

*Fig. 2—Comparison of subjective responses to military aircraft noise between two different sound recording/playback techniques (Real line and triangular symbol represents regression model and observed data when subjects were tested through sound recorded by a dummy head, respectively. Dotted line and rectangular symbol represents regression model and observed data when subjects were tested through sound recorded by a single microphone, respectively).*

This means that the regression models for the two categories (sound recording by the single microphone and by the dummy head) have the same intercept but different slopes for all four noise sources. Figures 1–5 show the differences in the annoyance responses according to sound recording/playback technique for each noise group. The extent of annoyance to the sounds recorded with the dummy head was higher than that to the sounds recorded with the single microphone. It could be seen from Eq. (4) that the difference in the annoyance scores between two categories is given by the term $b_2 L_{Aeq}$. It was expected that this term would reflect binaural effects. Moreover, $b_2$, which was the regression coefficient of interaction term, was similar for each noise source; $b_2$ is 0.012 in commercial aircraft noise group (A), 0.011 in military aircraft noise group (B) and 0.01 in railway and road traffic noise groups (C, D).

Let binaural effects be defined as the difference in the variations in the annoyance scores between two categories when $L_{Aeq}$ is varied by $\Delta L_{Aeq}$ from the specified noise level. For example, when $L_{Aeq}$ was increased by $\Delta L_{Aeq}$ from the specified noise level, the binaural effect caused an increase in the annoyance response by as much as an additional $0.01\Delta L_{Aeq}$. Figure 5 explains in more detail the binaural effects (difference between Δ A1 and Δ A0) defined in this paper. Note that the binaural effects explained in this paper are based on from 0 to 10 annoyance scale.

## 5 CONCLUDING REMARKS

Noise measurements have been carried out with a single microphone and noise metrics have been calculated based on input signals from the single microphone. However, people hear sound that has been distorted by binaural effects. This fact means that subjective response graphs (noise levels vs. annoyance responses) represent the relation between noise levels and their corresponding annoyance responses plus binaural effects.

In this paper, the binaural effect was defined as not a physical quantity but as a psychological (or subjective) quantity. For the purpose of demonstrating the significance of binaural effect and evaluating the binaural effect as a psychological quantity, a laboratory study was conducted using headphone simulation in the

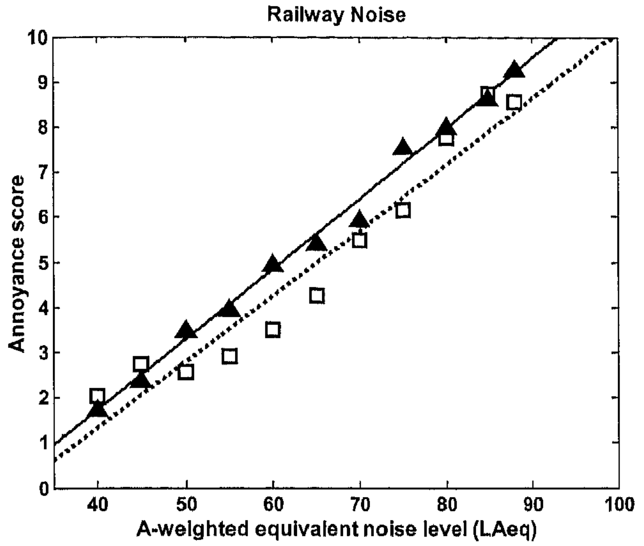

*Fig. 3—Comparison of subjective responses to railway noise between two different sound recording/playback techniques (Real line and triangular symbol represents regression model and observed data when subjects were tested through sound recorded by a dummy head, respectively. Dotted line and rectangular symbol represents regression model and observed data when subjects were tested through sound recorded by a single microphone, respectively).*

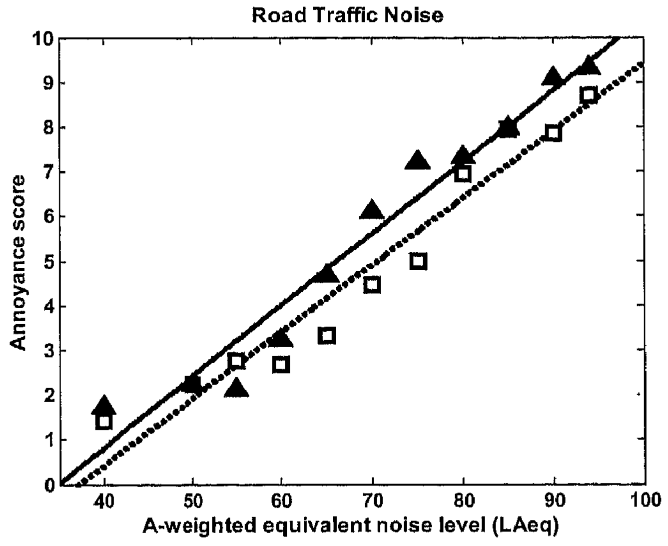

*Fig. 4—Comparison of subjective responses to road traffic noise between two different sound recording/playback techniques (Real line and triangular symbol represents regression model and observed data when subjects were tested through sound recorded by a dummy head, respectively. Dotted line and rectangular symbol represents regression model and observed data when subjects were tested through sound recorded by a single microphone, respectively).*

anechoic chamber. Of course, there were some limitations in these tests. Except for prior mentioned things (see Secs. 1 and 2.1), sound attenuation with propagation in each frequency band was not considered in detail.

However, important results could be acquired from laboratory tests in spite of these limitations. For the four noise sources, it was found that the mean annoyance scores for signals recorded with a single microphone and with a dummy head were significantly different. Binaural effects were defined as the difference of annoyance variations between two sub-groups when $L_{Aeq}$ was varied by $\Delta L_{Aeq}$ from the specified noise level. The predictors were $L_{Aeq}$ and $L_{Aeq}$* *Technique* in resultant regression of four noise sources, where *Technique* is zero for recording with the single microphone and one for recording with the dummy head. The regression coefficients of $L_{Aeq}$* *Technique* in four model equations for the four transportation noise sources explained the extent of binaural effect. In the four model equations showed a value for $b_2=0.01$, indicating that annoyance increased faster by about 1% with than without the binaural effect. Binaural effect could be expressed as $0.01\Delta L_{Aeq}$ on the basis of from 0 to 10 annoyance scale.

However, it would be too early to conclude that binaural effect was $0.01\Delta L_{Aeq}$. It is necessary that the quantity of the binaural effect be verified through more studies in more realistic environments.

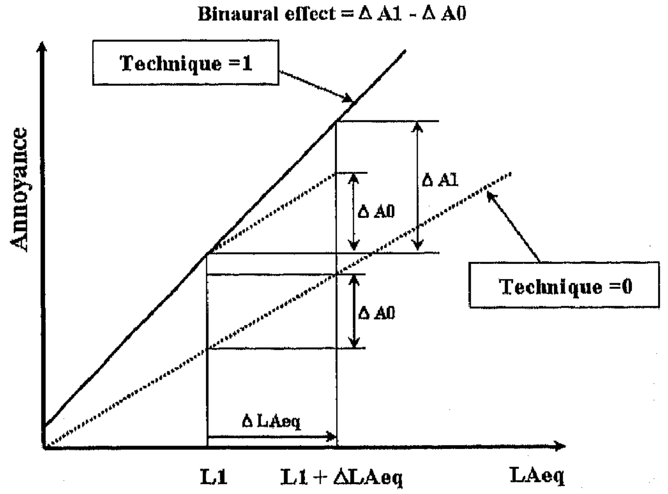

*Fig. 5—Geometric description of binaural effects defined in this paper.*

## 6 ACKNOWLEDGMENTS

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