Noise-induced annoyance from transportation noise: Short-term responses to a single noise source in a laboratory

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An experimental study was performed to compare the annoyances from civil-aircraft noise, military-aircraft noise, railway noise, and road-traffic noise. Two-way within-subjects designs were applied in this research. Fifty-two subjects, who were naïve listeners, were given various stimuli with varying levels through a headphone in an anechoic chamber. Regardless of the frequency weighting network, even under the same average energy level, civil-aircraft noise was the most annoying, followed by military-aircraft noise, railway noise, and road-traffic noise. In particular, penalties in the time-averaged, A-weighted sound level (TAL) of about 8, 5, and 5 dB, respectively, were found in the civil-aircraft, military-aircraft, and railway noises. The reason could be clarified through the high-frequency component and the variability in the level. When people were exposed to sounds with the same maximum A-weighted level, a railway bonus of about 3 dB was found. However, transportation noise has been evaluated by the time-averaged A-weighted level in most countries. Therefore, in the present situation, the railway bonus is not acceptable for railway vehicles with diesel-electric engines.

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I. INTRODUCTION

Most research on the effects of transportation noise has been performed in advanced western countries or the EU and US. The majority of papers have reported that aircraft noise is the most annoying and railway noise is the least annoying.[1–3] The "railway bonus" refers to the fact that railway noise is less annoying than other transportation noise. However, several studies have revealed somewhat contradictory results.[4–6]

Recent field studies in Korea[7–9] have yielded different results with regard to dose-response relationships and the railway bonus in comparison with those in western countries.[3,5] Annoyance responses to aircraft and railway noise in Korea were higher than in western countries.[7,8] Road-traffic noise in Korea causes less sleep disturbance than railway noise and the self-reported sleep disturbance from road-traffic noise in Korea is similar to that in European countries.[9] Bonus effects were found not for railway noise but for road-traffic noise. The results of Japanese studies were similar to the Korean results.[7] Railway noise in Japan caused annoyance that was much higher than in European countries. The response to railway noise in Japan is reportedly about 10 dB higher than that to road-traffic noise.[10] Hui and Yano[11] suggested the possibility of a railway bonus in the case of auditory tasks and the impossibility of a railway bonus in the case of non-auditory tasks. In their experiments, road-traffic noise and railway noise were presented as maskers of speech signals. It was reported that in the context of auditory tasks, the cause of a railway bonus was masking effects.

The majority of investigations on the impacts on transportation noise have found that aircraft noise causes the greatest annoyance. There has been a great diversity of opinion about the impacts of ground vehicles (especially with regard to railway noise). Although a bonus of 5 dB has been applied to railway noise in many EU countries, it seems that railway bonuses are controversial and not justified in every situation. In Ref. 12, railway bonuses have not been applied to all types of railway vehicle but restricted to electric railway vehicles with 12–20 cars and speeds of less than 250 km/h.

This is a very complex problem. The annoyance response is affected by not only acoustical components but also non-acoustical factors that are social, environmental, psychological, and economic in nature.[13,14] Even with similar noise levels and sources, the annoyance response differs across countries because the annoyance response to noise is affected by several external factors including the source's spectral difference, cultural differences, language differences, variations in survey questions, and differences in climatic conditions.[13,14] More detailed studies for various types of vehicle should be carried out in diverse environments.

In the present experimental research, annoyance from four kinds of transportation noise was investigated in order to compare the responses for the respective noise sources. The cause of the differential response to noises was explored through an analysis of the factors that influence transportation noise annoyance. The possibility of railway bonuses is also discussed.

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II. CHOICE IN SOUND REPRODUCTION

When research on the evaluation of subjective responses to noise is carried out using a headphone and loudspeaker in a laboratory, recorded sounds should be played to the subjects. Researchers have adopted various methods for sound recording and playback. With regard to sound recording, the choice is between a conventional microphone and an artificial dummy head. In general, a conventional microphone (1/2 in. condenser microphone) is used for the objective evaluation of environmental noise. Sounds at the entrance of the outer ear are different from those that are recorded by a conventional microphone because of head-related transfer functions (HRTFs). The discrepancy between the two sounds is caused by natural acoustic phenomena around the human head. This implies that sound recordings using an artificial dummy head ensure a better laboratory environment. Empirically, Kim *et al.*[15] compared the responses to traffic sounds recorded by a conventional microphone with those to traffic sounds that were recorded by a dummy head. The subjective responses to transportation noise showed remarkable variations according to the manner of sound recording and reproduction. Transportation noise annoyance also increased faster, i.e., by about 1%, in the presence of the binaural effect.

The second choice concerns devices for sound reproduction, i.e., headphones vs loudspeakers. Loudspeakers usually have been used in many laboratory studies. For binaural synthesis, two loudspeakers are required and the trans-aural cross-talk should be removed by a robust cross-talk cancellation algorithm. Though trans-aural cross-talk is a serious problem in laboratory studies on the impacts of environmental noise, the requirement for binaural synthesis has not been mentioned in most research papers on the present topic. Loudspeakers offer the advantage of natural hearing situations and the disadvantages of acoustic quality control, such as binaural synthesis, and spatial limitations, e.g., hearing rooms. Headphones offer the advantage of acoustic quality control and the disadvantage of unnatural hearing situations.

III. METHOD AND MATERIALS

A. Measurement and stimuli

1. Binaural recording and noise measurement

In this study, four kinds of noise (civil- and military-aircraft noise, railway noise, and road-traffic noise) were recorded by head and torso simulator (HATS) (Brüel & Kjær Type 4100) in order that the binaural sounds (HRTF-filtered sounds) could be heard by subjects. At the same time, noise measurement (HRTF-unfiltered sounds) was carried out using a free-field microphone (Brüel & Kjær Type 4190) for calculating the corresponding noise metrics, which are predictor variables for explaining the noise-induced annoyance.

It is practically impossible for two devices to be located at the same position simultaneously. The close (side-by-side) arrangement of a microphone and a dummy head causes acoustical interference in the sound field around the microphone by the dummy head and vice versa. It is also inevitable that the dummy head obstructs the sound from reaching the microphone. However, the noises that reach the two measuring devices are almost the same because the measurements are performed in an open environment with no obstacles, and the noise source is almost equidistant from each measuring device. Further, in the present study, the free-field microphone was located about 5 m away from the dummy head parallel to the forward direction of the noise sources in order to decrease the acoustical interference in each sound field.[16]

The two devices were placed about 15 m away from the side of the road and railway and about 100 m away from the runway of military and civil aircraft. They were located at about 1.7 m above the ground. Their output terminals were directly connected to a B&K's data acquisition and analysis system platform named as PULSE (Brüel & Kjær Type 3560C), which provides the functions of sound recording and real-time monitoring, including an analysis of signals in the time and frequency domains. A single microphone and two microphones that were inserted in both ears of the dummy head were calibrated before the noise measurement and binaural recording. Each transportation noise was simultaneously sampled by a dummy head and a microphone every 1/2 s[16].

Civil-aircraft, military-aircraft, and railroad-vehicle sounds were recorded through one pass-by. The civil-aircraft, military-aircraft, and railway vehicles were operated by a turbo fan, turbo jet, and diesel-electric engine, respectively. The railway vehicle had eight cars (one locomotive and seven passenger cars). The velocities of the aircraft and the railway vehicle were about 250 and 80–100 km/h, respectively. Road-traffic sound was recorded from a continuous stream of vehicles on the highway, whose velocities ranged from 80 to 120 km/h. This was done for considering general noise generation/exposure patterns that included both intermittent (aircraft and railway noises) and continuous (road-traffic noise) noises.

2. Test stimuli

The process for the construction of the test stimuli was as follows. An A-weighting network filter was constructed for calculating the time-averaged A-weighted sound level (TAL) for 15 s, $L_{A\mathrm{eq},15\ \mathrm{s}}$. The original signals (HRTF-unfiltered signals) were measured by a microphone pass through the filter. After this process, $L_{A\mathrm{eq},15\ \mathrm{s}}$ was calculated. The original values of the acoustic pressure (HRTF-unfiltered signals) were multiplied in order to change them into signals with the specific TAL value. These coefficients were acquired through MATLAB version 6.5 using the mathematical expression for the TAL for T s, $L_{A\mathrm{eq},T}$. Then, the coefficients were also multiplied with the signals (HRTF-filtered acoustic pressure) that were recorded by the two microphones in the ears of the dummy head. A total of 36 stimuli (nine stimuli per noise source) with various noise levels were generated and converted into 36 wave files. The stimuli of civil- and military-aircraft, railway, and road-traffic noises were generated in increments of 5 dB in TAL from 50 to 85 dB. Additionally, a stimulus with a TAL of 40 dB was generated for each noise source.

The durations of stimuli might be contentious with regard to the reliability of annoyance ratings because of the

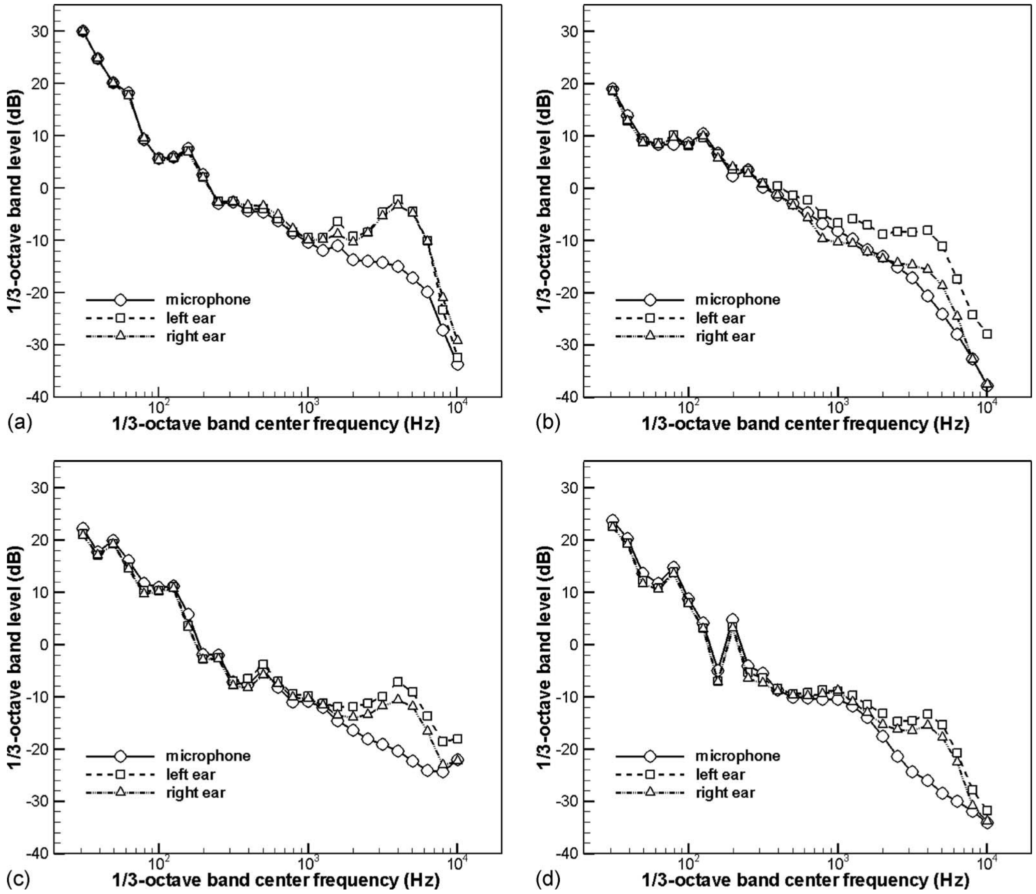

FIG. 1. Spectral difference between signals of a conventional microphone and both ears of HATS for (a) spectra of civil-aircraft noise, (b) spectra of military-aircraft noise, (c) spectra of railway noise, and (d) spectra of road-traffic noise. For all panels, 1/3-octave band levels were normalized to their time average A-weighted sound levels for 15 s.

varying exposure times that are encountered in real situations. In this study, the exposure time is considered by just one pass-by intermittent source in a general operating condition. Poulsen[16] reported that the exposure time did not have a significant effect on annoyance ratings. The choice of duration in the present study could be justified.

As shown in Fig. 1, the spectra of the stimuli differed from the signals that were measured by a conventional microphone. In particular, an acoustical boost by the pinna was found in the high-frequency bands. The TAL of stimuli was a little higher than that of the signals that were measured by the microphone. The level difference was less than 3 dB. The A-weighted statistical levels were found by means of Fig. 2. All the levels were acquired by exponential averaging every 1/8 s. For civil-aircraft, military-aircraft, railway, and road-traffic noises, the differences in levels between L10 and L50 were 12.8, 13.5, 11.7, and 1.3 dB, respectively, and between L10 and L90 were 24.5, 28.9, 25.3, and 3.6 dB, respectively.

B. Apparatus

1. Test section

An anechoic chamber was used as the test room for not only the audiometric screening test but also the subjective test in order to keep subjects from being disturbed by unwanted external sounds. The size of the anechoic chamber was $4.1\times4.1\times3.2\ \mathrm{m}^3$ and that of the test section was $3.2\times3.2\times2.1\ \mathrm{m}^3$. The absorbent material of the chamber was urethane foam. The cut-off frequency was approximately 200 Hz. Background noise in the anechoic chamber was less than 20 dB.

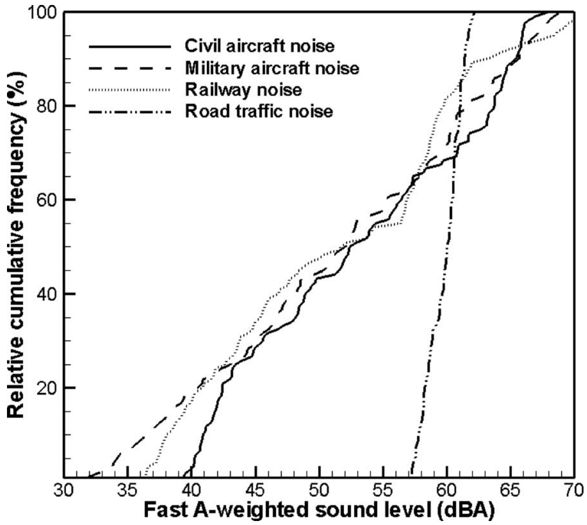

FIG. 2. Relative cumulative frequency of each transportation noise with time average A-weighted sound level 60 dB. Time integration was set to be fast (1/8 s exponential average). They were measured by a microphone, not an artificial dummy head (HATS).

2. Sound reproduction system

A system that could control the sound through a desktop personal computer (PC) (Pentium IV) with a RME's DIGI 96 Pro sound card was constructed in order to test the subjective responses to transportation noise. The output terminal of the sound card in the PC was connected to the front end of a power amplifier. The output stage of the power amplifier was interfaced with a headphone (Sennheiser HD25).

Each piece of the equipment for sound reproduction distorted the original input sound due to its frequency response; the distorted sound might have had a bad effect on the laboratory test. The sound field between the pinnae and ear couplers of the headphone distorted the sound. Therefore, acoustical correction had to be performed for the reliability of this research. A headphone was put on HATS and the output terminal of HATS was connected to the input terminal of PULSE (Brüel & Kjær Type 3560 C) for monitoring the output sound in terms of both the time and frequency domains. Sound monitoring was conducted using white noise as the input sound. The level differences between the input and output sounds in each frequency component were found to range from 20 Hz to 2 kHz. They were added to the test stimuli using a software (COOL EDIT PRO version 2.0) prior to the subjective test.

There was only one headphone in the anechoic chamber. Other devices were put out of the chamber so that subjects would not be disturbed by the noise from the sound reproduction equipment, such as fan noise in the computer, noise by operators, etc.

C. Participants

Fifty-two naïve subjects (32 male and 20 female) participated in the laboratory study. Their ages ranged from 20 to 35 years. The mean age was 26 and the standard deviation of the age was 3.2. Males were between 20 and 33 years of age (mean of 26.3 and standard deviation of 2.8). Females were between 21 and 35 years of age (mean of 25.6 and standard deviation of 3.8). All the participants had normal hearing [i.e., the hearing level (HL) was smaller than 15 dB of the reference equivalent threshold sound pressure level[17] in this research]. They were paid fees for their participation.

D. Laboratory test

1. Procedure of the laboratory test

All the subjects were screened audiometrically in order to filter participants who had abnormal hearing. The audiometric screening test was performed in the octave band center frequency between 20 Hz and 20 kHz according to the ascending method in Ref. 18. After the audiometric screening test, subjects were instructed on the procedure and experimental method. The main instructions were as follows.

- Whatever makes a noise or disturbs the experiment should not be permitted in the test section.
- Annoyance is different from the loudness of each noise event. Thus, the level or loudness of each presented sound must not be considered as the reference.

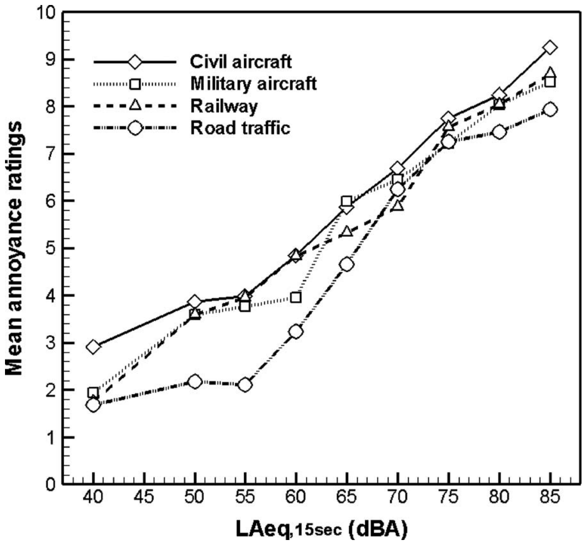

FIG. 3. Mean annoyance ratings for civil-aircraft noise, military-aircraft noise, railway noise, and road-traffic noise as a function of the time average A-weighted sound level of each noise.

- Annoyance is defined as a feeling of displeasure that is evoked by a noise or any feeling of resentment, displeasure, discomfort, and irritation when a noise intrudes into someone's thoughts and moods or interferes with their activity.
- Subjects may imagine reading a book, watching TV, or any similar activity.
- The scoring of annoyance on the questionnaire should be performed when no sound is heard following the respective noise event.

Integers between 1 and 36, inclusive, were assigned to all 36 stimuli. Random permutations of the integers between 1 and 36, inclusive, were generated using MATLAB. Each subject was presented with 36 stimuli in a random order. Each stimulus lasted for 15 s. Subjects evaluated the annoyance from each stimulus on the questionnaire for 15 s. Each experiment lasted about 90 min, including hearing tests and rest breaks.

2. Questionnaire and rating scale

The questionnaire included questions about the participant's age, gender, Weinstein's[19] noise sensitivity, and annoyance. Subjects were asked to answer the question in Korean, which translated to "What extent of annoyance would you feel if you had heard the noise in your common environment?" in English. They marked the extent of annoyance in the questionnaire after hearing each stimulus. In their study, Fields *et al.*[20] reported that a 0–10 numerical scale is likely to be easily understood by people of all countries and cultures who are familiar with currencies in a base-10 monetary system and other familiar counting situations. Team 6 of the International Commission on the Biological Effects of Noise (ICBEN) recommended a five-point (Not at all–Slightly–Moderately–Very–Extremely) verbal and a 0–10 (0 means "Not at all" and 10 means "Extremely") numerical scale for community annoyance ratings. Therefore, a 0–10

TABLE I. Mauchly's tests of sphericity. Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

Within-subject effects	Mauchly's W	Approx. chi-square	df	Sig.	Huynh–Feldt's epsilon
Noise level	0.186	80.915	35	<0.001	0.785
Vehicle type	0.841	8.614	5	0.126	0.943
Noise level*vehicle type	<0.001	608.129	299	<0.001	0.532

numerical scale was used as the annoyance rating scale in this research. The end points of this scale were labeled with the Korean equivalents of "not annoyed at all" and "very annoyed," respectively. The choice for the 11-point numerical scale is based on the assumption that respondents are more cognitively familiar with 0–10 scaling than with the shorter seven- or nine-point numeric scales.[21]

Weinstein's noise sensitivity scale (0–105) consists of 21 items, most of which express attitudes toward noise in general and emotional reactions to a variety of environmental sounds that are encountered in the everyday lives of students, who are the target population of the questionnaire.[22] For every statement, six response options ranging from strong disagreement to strong agreement are presented.[22] In 14 of the 21 items, agreement with the item indicates greater noise sensitivity of the respondent.[23]

IV. ANALYSIS AND RESULTS

A. Comparison across vehicle types

For civil-aircraft, military-aircraft, railway, and road-traffic noises, the mean annoyance ratings of subjects, as a function of the TAL of each noise, are shown in Fig. 3. Civil aircraft was more annoying than the other sources, while road traffic was the least annoying of all. Main (noise level and vehicle type) and interaction effects were tested in a repeated measure Analysis of Variance (ANOVA) (53 subjects × 4 vehicle types × 9 noise levels).

The assumptions in tests of within-subject effects are that the variances of the sets of data are equal (i.e., the errors are homoscedastic) and that the errors are uncorrelated with each other. Mauchly's test of sphericity is used to verify whether the assumptions of univariate models are met. If Mauchly's test shows violation of sphericity, this may be compensated by an epsilon adjustment. The correction is made by multiplying the degrees of freedom for the effect by the epsilon value and by multiplying the degrees of freedom for the error term by the epsilon value. The significance of the F-value is then determined using the corrected degrees of freedom. In this analysis, Huynh–Feldt's epsilon was used.

Tables I and II show the results of Mauchly's test of sphericity and within-subject effect tests, respectively. As shown, Mauchly's W for the vehicle type was not statistically significant ($p > 0.05$). The noise level and interaction (noise level*vehicle type) violated the sphericity assumption ($p > 0.05$). Huynh–Feldt's epsilon adjustment was required for the noise level and interaction. The F-test or adjusted F-test for two main effects and one interaction effect were statistically significant. The differences in the mean annoyance ratings across vehicle types were significant [$F(3,153) = 32.460$, $p < 0.001$]. The ratings increased with the time-averaged A-weighted sound levels [$F(6.728,320.155) = 319.179$, $p < 0.001$]. *Post hoc* pair-wise multiple comparison tests did not justify these conclusions at all paired conditions. The difference between military-aircraft noise and railway noise was not significant ($p > 0.05$). The mean annoyance ratings at the TAL of 50 dB were not significantly different from those at the TAL of 55 dB ($p > 0.05$). The mean annoyance ratings at the TAL of 75 dB were not significantly different from those at the TAL of 80 dB ($p > 0.05$). The mean annoyance ratings at the TAL of 80 dB were not significantly different from those at the TAL of 85 dB ($p > 0.05$). These results might be caused by nonlinearity, which asymptotically approaches either 0 (not annoyed at all) or 10 (very annoyed) at the lower and higher levels.

In Table III, it is seen that the slopes and intercepts in the linear annoyance models depend on the vehicle type. In

TABLE II. Repeated measure two-way ANOVA. Noise level and noise level*vehicle type violated sphericity assumption. F-tests adjusted by Huynh–Felt's epsilon for them were conducted. Vehicle type satisfied sphericity assumption.

Source		Sum of square	df	Mean square	F	Sig.
Noise level	Sphericity assumed	8818.779	8	1102.347	319.179	<0.001
	Huynh–Feldt	8818.779	6.278	1404.814	319.179	<0.001
Error (noise level)	Sphericity assumed	1409.110	408	3.454		
	Huynh–Feldt	1409.110	320.155	4.401		
Vehicle type	Sphericity assumed	340.312	3	113.437	32.460	<0.001
	Huynh–Feldt	340.312	2.829	120.301	32.460	<0.001
Error (vehicle type)	Sphericity assumed	534.668	153	3.459		
	Huynh–Feldt	534.668	144.270	3.706		
Noise level*vehicle type	Sphericity assumed	171.832	24	7.160	2.195	0.001
	Huynh–Feldt	171.832	12.778	13.447	2.195	0.009
Error (noise level*vehicle type)	Sphericity assumed	3393.168	1224	3.262		
	Huynh–Feldt	3393.168	651.697	6.127		

TABLE III. Linear least-squares fit for source-specific and overall data. Dependent variable is mean annoyance ratings, and independent variable is L_{Aeq} (mean annoyance ratings$=b_0+b_1*L_{Aeq}$). Mean and σ_e are annoyance rating averaged across 52 subjects and standard error of the estimated annoyance ratings in each vehicle or total, respectively. DW is Dubin–Watson's D statistic.

Vehicle type	b_1	b_0	r	Mean	σ_e	DW
Civil aircraft	0.148	−3.599	0.698	5.934	2.101	1.871
Military aircraft	0.153	−4.337	0.735	5.496	1.949	1.704
Railway	0.154	−4.420	0.751	5.513	1.877	1.785
Road traffic	0.166	−5.972	0.765	4.750	1.943	1.656
Overall	0.155	−4.582	0.730	5.423	2.014	1.677

the road-traffic noise model, the slope was the steepest and the intercept was the smallest. In the civil-aircraft noise model, the slope was the gentlest and the intercept was the greatest. The railway and military-aircraft noises were moderate in both. The differences in the annoyance responses to noise sources increased as the corresponding TALs decreased. In view of psychometrics, the TAL of the equally annoying road-traffic noise is larger than those of the civil-aircraft, military-aircraft, and railway noises. Penalties should be added to the TALs of civil-aircraft, military-aircraft, and railway noises in relation to the differences in levels. The penalties for the civil-aircraft, military-aircraft, and railway noises are $14.295-0.108L_{Aeq}$, $9.849-0.078L_{Aeq}$, and $9.349-0.072L_{Aeq}$, respectively. The overall mean annoyance rating was about 5 (more precisely, the expected mean annoyance was 5.423, as shown in Table III). In the model of civil-aircraft, military-aircraft, and railway noises, each of the TALs of 58.1, 61.0, and 61.2 dB caused an expected annoyance of 5. The penalty for the civil-aircraft noise compared with community responses to road-traffic noise was a TAL of 8 dB on the average. The penalty for the military-aircraft and railway noises compared with the subjective responses to road-traffic noise was a TAL of 5 dB on the average.

B. Comparison in terms of other noise rating indices

1. Other A-weighted noise ratings

Various A-weighted noise metrics, such as MXAL, modified TAL, NPL, and TNI, were investigated. The time weighting was set to "fast" (125 ms) for their calculation. In this research, the difference between ASEL and TAL was a constant of 11.76 dB; thus, the two indices were perfectly correlated. Therefore, ASEL was excluded from the analysis. The modified TAL, NPL, and TNI are computed from the following formula. The noise metric for each stimulus is summarized in Table IV.

$$L_{Aeq}{}' = L_{Aeq} + f(\sigma'), \qquad (1)$$

where

$$\sigma' = \left[\frac{1}{T}\int_0^T \left(\frac{dL}{dt}\right)^2 dt\right]^{0.5}. \qquad (2)$$

Further,

$$f(\sigma') = 10\log_{10}(1+15\sigma') \qquad (3)$$

and

$$\mathrm{NPL} = L_{Aeq} + k\sigma. \qquad (4)$$

In the above, k is an empirical constant, which is set equal to 2.56, and σ is the standard deviation.

$$\mathrm{TNI} = 4(L_{10}-L_{90}) + (L_{90}-30). \qquad (5)$$

Regression analyses regarding the four independent variables, except for ASEL, were performed for each noise source and for all noise sources taken together. In Table V, the correlation between annoyance for the overall noise source and TNI was extremely poor: TNI explained only 16.6% of the variance in annoyance, which means that TNI is not a good noise metric and that further analysis is meaningless. The correlation between the modified TAL and annoyance ratings was significantly different from the correlation between the NPL and annoyance ratings (Fisher's $Z=3.770$, $p<0.001$). The correlation between TAL (or ASEL) and the annoyance ratings was significantly different from the correlation between the NPL and annoyance ratings (Fisher's $Z=3.440$, $p<0.001$). The differences in the goodness of fit between ASEL, TAL, MXAL, and the modified TAL were not statistically significant ($Z=0.133-0.463$, $p>0.05$).

Consequently, TAL, ASEL, MXAL, and the modified TAL might be relatively good acoustic measures for annoyance responses to short-term exposure to community noise. Thus, TNI and NPL were no longer taken into account. Annoyance responses to each noise were compared regarding the two noise metrics.

a. Maximum A-weighted sound level ($L_{A\max}$) The penalties for civil-aircraft, military-aircraft, and railway noises were $9.367-0.108L_{A\max}$, $4.090-0.078L_{A\max}$, and $1.988-0.072L_{A\max}$, respectively. In the model of civil-aircraft, military-aircraft, and railway noises, each of the maximum A-weighted sound levels of 66.1, 69.7, and 71.5 dB caused an expected annoyance of 5. The civil-aircraft penalty was a maximum A-weighted sound level of 2 dB on the average. The railway bonus was a maximum A-weighted sound level of 3 dB on the average. No bonus or penalty was found for military aircraft. Even with the same maximum A-weighted level, civil-aircraft noise was the most annoying, followed by road-traffic, military-aircraft, and railway noises, in that order.

TABLE IV. Summary of the levels in each noise metric for every stimuli.

Type of stimulus	L_{Aeq}	$L_{A\max}$	L_{Aeq}'	L_{NP}	TNI	L_{Beq}	L_{Ceq}	L_{Deq}	L_{Zeq}
Civil aircraft	40	48	60.7	63.4	89	41.6	43.3	46	43.8
	50	58	70.7	73.4	99	51.6	53.3	56	53.8
	55	63	75.7	78.4	104	56.6	58.3	61	58.8
	60	68	80.7	83.4	109	61.6	63.3	66	63.8
	65	73	85.7	88.4	114	66.6	68.3	71	68.8
	70	78	90.7	93.4	119	71.6	73.3	76	73.8
	75	83	95.7	98.4	124	76.6	78.3	81	78.8
	80	88	100.7	103.4	129	81.6	83.3	86	83.8
	85	93	105.7	108.4	134	86.6	88.3	91	88.8
Military aircraft	40	48.9	63.7	66.7	102.4	42.3	43.4	44.7	43.5
	50	58.9	73.7	76.7	112.4	52.3	53.4	54.7	53.5
	55	63.9	78.7	81.7	117.4	57.3	58.4	59.7	58.5
	60	68.9	83.7	86.7	122.4	62.3	63.4	64.7	63.5
	65	73.9	88.7	91.7	127.4	67.3	68.4	69.7	68.5
	70	78.9	93.7	96.7	132.4	72.3	73.4	74.7	73.5
	75	83.9	98.7	101.7	137.4	77.3	78.4	79.7	78.5
	80	88.9	103.7	106.7	142.4	82.3	83.4	84.7	83.5
	85	93.9	108.7	111.7	147.4	87.3	88.4	89.7	88.5
Railway	40	50.3	62	65	89.5	42.7	44.9	45.1	45.2
	50	60.3	72	75	99.5	52.7	54.9	55.1	55.2
	55	65.3	77	80	104.5	57.7	59.9	60.1	60.2
	60	70.3	82	85	109.5	62.7	64.9	65.1	65.2
	65	75.3	87	90	114.5	67.7	69.9	70.1	70.2
	70	80.3	92	95	119.5	72.7	74.9	75.1	75.2
	75	85.3	97	100	124.5	77.7	79.9	80.1	80.2
	80	90.3	102	105	129.5	82.7	84.9	85.1	85.2
	85	95.3	107	110	134.5	87.7	89.9	90.1	90.2
Road traffic	40	42.2	57.5	43.4	22.2	42.1	43.8	44	44.2
	50	52.2	67.5	53.4	32.2	52.1	53.8	54	54.2
	55	57.2	72.5	58.4	37.2	57.1	58.8	59	59.2
	60	62.2	77.5	63.4	42.2	62.1	63.8	64	64.2
	65	67.2	82.5	68.4	47.2	67.1	68.8	69	69.2
	70	72.2	87.5	73.4	52.2	72.1	73.8	74	74.2
	75	77.2	92.5	78.4	57.2	77.1	78.8	79	79.2
	80	82.2	97.5	83.4	62.2	82.1	83.8	84	84.2
	85	87.2	102.5	88.4	67.2	87.1	88.8	89	89.2

b. Modified time-averaged A-*weighted sound level* (L_{Aeq}')*: The modified TAL* The penalties for civil-aircraft, military-aircraft, and railway noises were $13.349-0.108L_{Aeq}'$, $5.590-0.078L_{Aeq}'$, and $6.434-0.072L_{Aeq}'$, respectively. In the model of civil-aircraft, military-aircraft, and railway noises, each of the modified TALs of 78.8, 84.7, and 83.2 dB caused an expected annoyance of 5. The civil-aircraft penalty was a modified TAL of 5 dB on the average. No bonus or penalty was found for either military-aircraft or railway noise (less than 2 dB).

2. Other frequency weighting networks

The time-averaged B-, C-, D-, and Z-weighted sound levels were computed for all stimuli (see Table IV). The least-squares fit was performed between the annoyance ratings and each of the sound levels. The variances of the annoyance explained by L_{Beq}, L_{Ceq}, L_{Deq}, and L_{Zeq} were 0.530 ($r=0.728$), 0.530 ($r=0.728$), 0.542 ($r=0.736$), and 0.530 ($r=0.728$), respectively. No significant difference was found in the goodness of fit across the sound levels ($p>0.05$). They were not significantly different from the product-moment correlations between relatively good acoustic measures (L_{Aeq}, L_{AE}, $L_{A\max}$, and L_{Aeq}') and the annoyance response ($p>0.05$).

The penalties or bonuses of civil-aircraft, military-aircraft, and railway noises are shown in Table VI. For the noise metrics, the civil-aircraft penalties were $15.127-0.108L_{Zeq}$, $14.958-0.108L_{Beq}$, $15.175-0.108L_{Ceq}$, and $12.880-0.108L_{Deq}$, respectively. The military-aircraft penalties were $10.807-0.078L_{Zeq}$, $9.837-0.078L_{Beq}$, $10.494-0.078L_{Ceq}$, and $9.500-0.078L_{Deq}$, respectively. The railway penalties were $8.792-0.072L_{Zeq}$, $8.952-0.072L_{Beq}$, $8.590-0.072L_{Ceq}$, and $8.560-0.072L_{Deq}$, respectively. On average, the civil-aircraft penalties were about 8 dB for the B-, C-, and Z-weighted L_{eq} and about 6 dB for the D-weighted L_{eq}. On average, the military-aircraft penalties were about 5 dB

TABLE V. Linear least-squares fit for source-specific and overall data. Dependent variable is mean annoyance ratings, and independent variable is each A-weighted noise metric (mean annoyance ratings$=b_0+b_1*$noise metric). r is product-moment correlation, r^2 is the ratio of variance accounted for by regression to total variance, and σ_e is standard error of the estimated annoyance ratings in each vehicle or total.

Vehicle type	Noise metric	b_1	b_0	r	r^2	σ_e
Overall	$L_{A\,\max}$	0.153	−5.568	0.737	0.543	1.990
Civil aircraft		0.148	−4.783	0.698	0.488	2.101
Military aircraft		0.153	−5.659	0.735	0.541	1.949
Railway		0.154	−6.008	0.751	0.564	1.877
Road traffic		0.166	−6.338	0.765	0.585	1.943
Overall	$L_{A\mathrm{eq}}{}'$	0.154	−7.761	0.735	0.540	1.996
Civil aircraft		0.148	−6.664	0.698	0.488	2.101
Military aircraft		0.153	−7.952	0.735	0.541	1.949
Railway		0.154	−7.812	0.751	0.564	1.877
Road traffic		0.166	−8.880	0.765	0.585	1.943
Overall	L_{NP}	0.118	−4.515	0.673	0.453	2.179
Overall	TNI	0.035	1.915	0.408	0.166	2.689

for the B- and C-weighted L_{eq}, about 4 dB for the D-weighted L_{eq}, and about 6 dB for the Z-weighted L_{eq}. On average, the railway penalty was about 4 dB for the B-, C-, D-, and Z-weighted L_{eq}. These results are similar to the results when the A-weighted L_{eq} was controlled. The civil-aircraft noise was the most annoying, the military-aircraft and railway noises were moderate, and the road-traffic noise was the least annoying.

C. Effects of factors on annoyance

1. Acoustical factors

The influence of several acoustical factors on annoyance was investigated using principal component factor and multiple regression analyses. A total of seven factors, such as TAL ($L_{A\mathrm{eq}}$), MXAL ($L_{A\,\max}$), $L_{A\,\max-A\mathrm{eq}}$, σ, σ', L_{C-A}, and L_{D-B}, were selected. The differences between the C- and A-weighted equivalent continuous levels (L_{C-A}) represented the low-frequency content in the respective transportation noises. The differences between the D-weighted and B-weighted equivalent continuous levels (L_{D-B}) represented the high-frequency content in the respective transportation noises.

A principal component factor analysis was performed for the seven factors in order to classify them into uncorrelated components. Three components accounted for 90% of

TABLE VI. Linear least-squares fit for source-specific and overall data. Dependent variable is mean annoyance ratings, and independent variable is each time average noise metric with regard to frequency weightings (mean annoyance ratings$=b_0+b_1*$noise metric). r is product-moment correlation, r^2 is the ratio of variance accounted for by regression to total variance, and σ_e is standard error of the estimated annoyance ratings in each vehicle or total.

Vehicle type	Noise metric	b_1	b_0	r	r^2	σ_e
Overall	$L_{B\mathrm{eq}}$	0.155	−4.897	0.728	0.530	2.018
Civil aircraft		0.148	−3.839	0.698	0.488	2.101
Military aircraft		0.153	−4.689	0.735	0.541	1.949
Railway		0.154	−4.836	0.751	0.564	1.877
Road traffic		0.166	−6.322	0.765	0.585	1.943
Overall	$L_{C\mathrm{eq}}$	0.155	−5.138	0.728	0.530	2.020
Civil aircraft		0.148	−4.081	0.698	0.488	2.101
Military aircraft		0.153	−4.858	0.735	0.541	1.949
Railway		0.154	−5.174	0.751	0.564	1.877
Road traffic		0.166	−6.600	0.765	0.585	1.943
Overall	$L_{D\mathrm{eq}}$	0.156	−5.431	0.736	0.542	1.994
Civil aircraft		0.148	−4.494	0.698	0.488	2.101
Military aircraft		0.153	−5.055	0.735	0.541	1.949
Railway		0.154	−5.211	0.751	0.564	1.877
Road traffic		0.166	−6.632	0.765	0.585	1.943
Overall	$L_{Z\mathrm{eq}}$	0.155	−5.190	0.728	0.530	2.020
Civil aircraft		0.148	−4.156	0.698	0.488	2.101
Military aircraft		0.153	−4.873	0.735	0.541	1.949
Railway		0.154	−5.218	0.751	0.564	1.877
Road traffic		0.166	−6.667	0.765	0.585	1.943

TABLE VII. Rotated component matrix of principal component factor analysis. Three latent factors were extracted by Varimax rotation. They accounted for 90.0% (first factor: 40.7%, second factor: 28.3%, and third factor: 21.0%) of the trace of the matrix analyzed.

	Components		
Acoustical factor	1	2	3
L_{Aeq}	−0.053	0.998	0.002
$L_{A\,\max}$	0.162	0.987	−0.004
$L_{A\,\max-Aeq}$	0.983	0.057	−0.027
σ	0.984	0.052	0.172
σ'	0.871	0.032	−0.050
L_{C-A}	0.203	0.026	−0.857
L_{D-B}	0.293	0.027	0.840

the total variance. The first component represented the level variability, the second component represented the energy exposed, and the third component represented spectra (see Table VII). These findings were similar to Cermak and Cornillon's results.[23] L_{C-A} was negatively correlated with L_{D-B}. To avoid multicollinearity, multiple regression analyses were performed with independent variables, such as one factor of the exposed energy (L_{Aeq}), one factor of the level-variability property, and one factor of the spectral property (L_{C-A} or L_{D-B}). In Table VIII, it is seen that the rate of the explained variance increased by as much as 1.5% due to the level-variability property, 1.4% by the spectral property, and 2.0% by both. The regression coefficient of L_{C-A} was not significant ($p > 0.05$).

The L_{D-B} of civil-aircraft, military-aircraft, and railway noises were 2.56, 0.53, and 0.56 dB, respectively, larger than those of road-traffic noise. σ of civil-aircraft, military-aircraft, and railway noises were 7.79, 9.11, and 8.44 dB, respectively, larger than those of road-traffic noise. From the third row in Table VIII, it can be seen that aircraft noise annoyance was 0.637 (2.56×0.249) larger than road-traffic noise annoyance in terms of ΔL_{D-B} and 0.545 (7.79×0.07) larger than road-traffic annoyance in terms of $\Delta\sigma$. The total increase in the civil-aircraft noise annoyance was equivalent to a TAL of 7.6 dBA (≒8 dBA). The constitution and the proportion of penalty that is accounted for by each acoustical factor with regard to the noise source are summarized in Table IX. For other noise metrics, the cause of differential responses to noise sources could be analyzed similarly.

2. Individual noise sensitivity

Individual noise sensitivities for all subjects were investigated using Weinstein's method. Their median was 63, the lower quartile was 31.5, and the upper quartile was 84. Least-squares fits were performed for L_{Aeq} and noise sensitivity and undertaken for L_{Aeq}, L_{D-B}, σ, and noise sensitivity. The assumptions, such as linearity, independence, multicollinearity, etc., were not violated in both cases. The multiple correlations were 0.761 ($r^2 = 0.579$) and 0.775 ($r^2 = 0.600$). In both cases, the increase in multiple correlations was statistically significant ($Z = 2.242$, $p < 0.05$; $Z = 2.136$, $p < 0.05$). An increase of 4.6% was obtained in the explained variance. From the present and prior results, it was confirmed that the effect of individual noise sensitivity on annoyance was more than those of the two acoustical factors or their combination. However, individual noise sensitivity did not account for the difference in annoyance with regard to noise sources because a within-subject design was applied in this experiment.

TABLE VIII. Linear relationships between annoyance and indices for acoustical properties. r is multiple correlation, r^2 is the ratio of variance accounted for by regression to total variance, and σ_e is standard error of the estimate.

Linear relationships	r	r^2	σ_e
$\text{Annoyance} = -5.601 + 0.155L_{Aeq} + 0.366L_{D-B}$	0.740	0.547	1.982
$\text{Annoyance} = -5.343 + 0.155L_{Aeq} + 0.099\sigma$	0.740	0.548	1.981
$\text{Annoyance} = -5.811 + 0.155L_{Aeq} + 0.070\sigma + 0.249L_{D-B}$	0.744	0.553	1.970

TABLE IX. Constitution and proportion of penalty by each acoustical factor with regard to noise source. Second column shows penalty caused by the difference between high-frequency components of each noise source and road traffic, and third column shows penalty caused by the difference between level variability of each noise source and road traffic.

Noise source	ΔL_{D-B} [dBA (%)]	$\Delta\sigma$ [dBA (%)]	Total penalty [dBA (%)]
Civil aircraft	4.1(53.9)	3.5(46.1)	7.6(100)
Military aircraft	0.9(18.0)	4.1(82.0)	5.0(100)
Railway	0.9(19.1)	3.8(80.9)	4.7(100)

V. DISCUSSION

Many investigations have been performed on comparing the annoyances from various types of vehicle. All of them affirm that vehicle noises cause differential levels of annoyance. However, there have been inconclusive and conflicting findings regarding the impact of railway noise.

Through a cluster of six different field surveys, Fields and Walker[1] compared railway noise annoyance with aircraft noise and road-traffic noise annoyance. In order to identify a systematic difference, the results of the six surveys were analyzed using identical noise and annoyance ratings. Railway noise annoyance was less than road-traffic and aircraft noise annoyances and increased less rapidly with the noise level. A railway bonus of about 10 dB was found. Miedema and Vos[3] synthesized 55 data sets that were acquired from different surveys. In spite of large variations in each data set for the same type of vehicle, the proposed dose-response relationships showed that railway noise caused the least annoyance and aircraft noise caused the greatest annoyance. The gap between road-traffic and railway noises was about 5 dB with respect to the road-traffic DNL of 60 dB. Finegold *et al.*[5] performed meta analysis for data based on Field *et al.* and developed source-specific dose-response relationships using a logistic model. The result of Finegold *et al.* was somewhat different from the two results referred above. At the higher level ($\text{DNL} > 75$ dB), railway noise caused more annoyance than road-traffic noise. At the lower level, the annoyances caused by both were not significantly different.

In a laboratory study by Öhström *et al.*,[4] annoyances from two types of road-traffic noise (lorry and moped noises), railway noise, and aircraft noise were tested. Under the condition of controlled TAL (L_{Aeq}), lorry noise was the least annoying, followed by railway, aircraft, and moped noises, in that order. Under the condition of controlled MXAL ($L_{A\max}$), lorry noise was the least annoying, followed by moped, railway, and aircraft noises, in that order. The differences were statistically significant. The two road-traffic vehicles caused different levels of annoyance. The reason might be the differing time patterns and spectral characteristics that are caused by engine types and operating conditions. Versfeld and Vos[24] demonstrated that driving conditions and the spectral difference significantly influenced the annoyance. From this point of view, it is necessary that the referred field surveys should be reanalyzed in more detail.

In this research, noise annoyances from four kinds of vehicle with specific types of engine were compared. Different results were revealed with regard to the noise metrics. When transportation noise was evaluated as the maximum A-weighted level, civil-aircraft noise caused the most annoyance, followed by road-traffic noise, military-aircraft noise, and railway noise, in that order. The railway bonus was about 3 dBA with regard to the maximum A-weighted level. However, the railway bonus was not found for other noise metrics. Despite the same time-averaged (or exposure) level, it was found that aircraft noise was the most annoying and road-traffic noise was the least annoying. The civil-aircraft penalty was a TAL of about 8 dBA that was caused by the high-frequency component (53.9%) and level variability (46.1%). The military-aircraft penalty was a TAL of about 5 dBA that was caused by the high-frequency component (18.0%) and level variability (82.0%). The railway penalty was a TAL of about 5 dBA that was caused by the high-frequency component (19.1%) and level variability (80.9%) (see Table IX). Not only the exposure (or average) energy level but also the peak energy level might be important in the situation of short-term exposure of noise because people hear the peak level instantaneously. Two standard noise regulations with regard to the maximum noise level and the average noise level will be necessary. However, transportation noise has been evaluated by only the TAL in most countries, including Korea. Therefore, the railway bonus will not be acceptable for railway vehicles with diesel-electric engines under an evaluation system that is based on the average noise level.

Recent field studies[7–9] justified these findings in Korea. In their researches, the difference in annoyance from each noise source (civil aircraft, railway, and road traffic) was not different from that in this research. Of course, it is difficult to compare the present research with the field researches directly. As known, there are various differences between the both in noise exposure and annoyance rating conditions, process of annoyance perceived, interference of other noise, and so on. In other words, outdoor instantaneous annoyance is rated, and subjects have not suffered from specific noise, and other background noises are not considered in this experiment, whereas indoor cumulative annoyance is rated by mental integrations, and respondents have suffered from specific noise, and interference of other background noises has an influence on annoyance ratings in the field studies. Therefore, relative difference in annoyance responses according to vehicle types between a laboratory study and field studies was compared. In the field studies, the engine type of each noise source was similar to (or the same as) that in the present laboratory study. Civil-aircraft noise caused more annoyance than railway noise,[7,8] and road-traffic noise was the least annoying (exposure-response relationship for road-traffic noise was not reported). Self-reported sleep disturbance from railway noise was higher than that from road-traffic noise.[9]

VI. CONCLUDING REMARKS

The main purpose of the present experimental study was to compare the annoyance responses to civil-aircraft noise, military-aircraft noise, railway noise, and road-traffic noise. It should be noted that the annoyances for specific types and operating conditions of four vehicles were measured in simulated outdoor conditions. The following conclusions were drawn from the results.

1. Civil-aircraft noise caused the most annoyance and road-traffic noise caused the least annoyance for the same TAL (L_{Aeq}). Almost equal annoyance was rated at the same TAL (L_{Aeq}) for the military-aircraft and railway noises.
2. To obtain equally annoying levels under road-traffic noise, a penalty of 8 dB [TAL, viz., (L_{Aeq})] should be applied to civil-aircraft noise; likewise, a penalty of 5 dB (L_{Aeq}) should be applied to the military-aircraft and railway noises.
3. The differential responses to the noises can be explained by the high-frequency component and level variability. The greater these factors are, the greater the annoyance that can be expected.
4. A railway bonus would not be acceptable for railway vehicles with diesel-electric engines under the noise-evaluation system that is based on metrics of average energy.

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