Classification of heavy-weight floor impact sounds in multi-dwelling houses using an equal-appearing interval scale

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Abstract

Classifications of heavy-weight floor impact sounds based on subjective responses were suggested by conducting two experiments. First, statements describing perceptual acoustic qualities related to floor impact sounds in residential buildings were collected and assessed with respect to the degree of annoyance levels. Equal-appearing interval scaling for indicating level of annoyance caused by floor impact sounds was then created using these statements. As a next step, heavy-weight floor impact sounds with different $L_{A,Fmax}$ and temporal decay rates (DRs) were evaluated in terms of annoyance using both the Likert scale and the equal-interval statement scale in laboratory conditions. Five categories for heavy-weight floor impact sounds were suggested based on the annoyance responses. The extent of acoustic comfort in each class was clearly captured by the statements related to the range of $L_{A,Fmax}$ for each class. Effects of DR and noise sensitivity on the classifications were significant. Differences between the class criteria for impact sounds with DR 60 dB/s and 30 dB/s were approximately 5 dBA. In addition, significant differences were found between the high and low noise sensitivity classification groups for impact sounds in the 50–60 dBA range.

Keywords: Floor impact sound, Annoyance, Classification, Building noise, Acoustic comfort, Equal-appearing interval scale

1. Introduction

In multi-story buildings, floor impact sounds from various activities such as walking, jumping, and dropping of lightweight objects are regarded as one of the most annoying noises from neighbors. In particular, they are the most annoying noise types in apartment buildings in Korea because multi-dwelling houses such as apartments account for approximately 60% of dwelling types in Korea; in apartment buildings, residents can be easily exposed to noise penetrating through floors and ceilings from neighboring upper and lower level households [1,2]. The number of complaints regarding floor impact sounds registered by residents in Korea in 2013 is nine times that registered in 2011; 362 and 3,271 complaints related to floor impact sounds were registered in the Ministry of Environment of Korea in 2011 and 2013, respectively. Heavy impact sounds generated by adults walking or children running and jumping accounted for 73% of the total number of complaints [3].

Standard impact sources for the measurement of floor impact sound are specified in ISO 10140-3 [4] (rubber ball and tapping machine), and KS 2810 [5] and JIS 1418 [6] (rubber ball, bang machine, and tapping machine). Standard tapping machines have been used as a lightweight impact source to mimic tapping from high-heeled footwear or dropping of objects, producing impact sounds of primarily high frequencies. For evaluating heavyweight floor impact sounds of low frequencies, standard impact sources such as bang machines and rubber balls have been used in Korea [7].

In general, for short-term exposure to impact sounds, the impact noise loudness is the most critical factor affecting perceived noise annoyance, and the perceived impact noise loudness may be affected, in turn, by maximal sound pressure level [8,9]. The single number quantity $L_{i,Fmax,AW}$ is specified in JIS A 1419-2 [10] and KS F 2863-2 [11] as a measure for evaluating heavy-weight floor impact sounds. $L_{i,Fmax,AW}$ is calculated by comparing the sound pressure levels in each octave-band from 63 Hz to 500 Hz with those of the inverse A-weighting curve in IEC 61672-1 [12] in order to reflect the acoustic characteristics of heavy-weight floor impact sounds with higher energy at low frequencies, considering the relative loudness perceived by the human ear. The Korean government has implemented criteria for authorization and management of block structures with floor impact sounds in multi-dwelling houses [13]; the acoustic criteria are divided into four categories for $L_{i,Fmax,AW}$, ranging from 40 dB to 50 dB with approximately 3 dBA intervals. In addition, Ministry of Environment of Korea has recently legislated acceptable limit noise levels for floor impact sounds as 57 dBA and 52 dBA of $L_{A,Fmax}$, for day and night periods, respectively, for reducing the conflicts among residents living in multi-dwelling houses [14]. The criteria related to the acoustic qualities of floor impact sounds, however, do not provide clear explanations and evidences related to perceptual quality of acoustic environments in dwellings.

In this context, some studies on perception of floor impact sounds were conducted to investigate classifications of floor impact sounds based on subjective responses to noise [2,15,16]. Jeon et al. [15] performed surveys and laboratory experiments for evaluating the extent of dissatisfaction with various indoor noise sources, and proposed four criteria for floor impact sounds based on the obtained dose-response relationships. Classification scheme for floor impact noise was determined based on the degree of satisfaction (20%, 40%, 60%, and 80%) corresponding to a specific sound level. Still, these criteria provide limited understanding of perceptual acoustic quality that is insufficient to laypeople, because the notion of percentage dissatisfaction is not only obscure but also difficult to relate to perceived acoustic quality, which dwellers experience in their real living environments. Thus, it is necessary to develop classifications of floor impact sounds that reflect perception of acoustic quality in dwellings by using expressions describing attitudes towards floor impact noises.

Aside from sound levels, other acoustic factors such as spectral, spatial, and temporal characteristics affect subjective responses to impact noises [9,17–19]. In particular, the temporal decay rates of impact sounds, which are determined by floor and building structural aspects and spatial characteristics of rooms, significantly affect perceived annoyance [18,19]. In addition, noise sensitivity is one of the critical non-acoustical factors affecting human reactions to noise [20–22]. A few studies, however, have addressed the effects of those factors on the impact noise classification.

Therefore, the present study aimed at suggesting acoustic criteria for heavy-weight floor impact sounds based on the perception of acoustic environment in a multi-dwelling house. To achieve this goal, two experiments were scheduled. In Experiment I, a survey was conducted for establishing equal-appearing interval scales for indicating annoyance levels of floor impact sounds by using various expressions describing attitudes toward noise in daily life. In Experiment II, an auditory experiment was performed for evaluating the annoyance of heavy-weight floor impact sounds at various sound pressure levels and temporal decay rates (DR) of sounds; the evaluation was performed by using both the Likert scale and the equal interval statement scale in laboratory conditions. Classification of heavy-weight floor impact sounds was then suggested based on the annoyance responses. In addition, we examined the effects of different factors, such as the temporal decay rate of sound and individual noise sensitivity, on the classification.

2. Experiment I: Equal-appearing interval scale

2.1 Method

In Experiment I, the method of equal-appearing interval (EAI) scale, which is a procedure attempting to divide any given attitude into a number of equal-appearing intervals, was applied for scaling the attitudes toward noise perception of floor impact sounds with a large set of statements [23]. The EAI scale assumes that any attitude involves a continuum ranging from the strongest possible appreciation of a value at one extreme to the strongest possible depreciation of that value at the other extreme. The EAI scale was constructed in three principal stages: 1) collecting the statements, 2) rating the statements, and 3) selecting the final scale of statements with equal interval.

2.2 Results

First, fifty statements describing the responses and attitudes of residents toward floor impact sounds were collected from various sources such as documents and reports related to noise complaints in dwellings. Statements containing expressions such as "annoying", "disturbing" and "disliking" were collected, which can appropriately represent the responses and opinions of residents regarding floor impact sounds [24]. Among the fifty statements, inappropriate statements that were unrealistic, too specific, or too ambiguous were removed. After the elimination process, thirty-three statements by Korean residents were selected for the experiment. Table 1 presents the collected statements translated into English.

As a next step, subjects rated each statement in terms of how much each statement indicates an annoying attitude towards floor impact sounds. Fifty subjects, aged from 18 to 51 (mean age = 26.5, standard deviation of age = 8.3), who have experienced floor impact sounds in apartments, evaluated each statement by using a 7-point scale (ranging from 0 for "not annoyed at all" to 6 for "extremely annoyed"). Scale values for each item were computed based on the survey results. Median value and interquartile range (IQR) were calculated for each statement according to Eq. (1), and the calculated values for each statement are listed in Table 1:

$$Q_p = L + \frac{pn_t - n_b}{n_p} \qquad (1)$$

In Eq. (1), Q_p is percentile, L is the lower exact limit, p is the proportion (25%, 50%, and

75%) of scores below the desired percentile, n_t is the overall number of scores in the distribution, n_b is the number of scores below the interval containing the desired percentile, and n_p is the number of scores in the interval containing the desired percentile.

Final statements for EAI scale were selected based on the median and IQR values of the statements. The median and IQR values indicate the scale value for each statement and its corresponding variance, respectively. Within each value, the statement that had the smallest IQR was selected. As a result, seven statements (A-G) that were at equal-appearing intervals across the range of medians were selected and are listed in Table 2; statement A, "The indoor environment is quiet" had scale value of 0.6 and statement G, "It is impossible for people to live here" had scale value of 5.3. The interval between scale values of adjacent items was approximately 0.8. The developed EAI scale for floor impact noise was used for evaluating floor impact sounds in Experiment II.

Table 1

Table 2

3. Experiment II: Classification of floor impact sounds

3.1. Method

3.1.1. Recording floor impact sounds

A rubber ball was used to generate heavy-weight floor impact sounds in the present study because physical properties of the rubber ball, including its mechanical impedance and impact force, were more similar to real impact sources than those of a bang machine [2,8,17]. The bang machine produces an impact force of 4,200 N, which is much larger than real impact forces, such as those of children running (600-1,000 N) and jumping (2,000-3,000 N) in residential buildings, whereas the impact ball generates similar sounds to real human impact sounds in terms of impact force (1,500 N) and frequency characteristics [2,25]. Heavy-weight floor impact sounds generated by the rubber ball were measured in box-framed type reinforced concrete structures where the concrete slab thickness of the apartments ranged from 150 mm to 180 mm. The rubber ball generated impact sounds from the center of the upstairs room and the impact sounds were recorded at the center of the room by using a 1/2 inch microphone (B&K type 4189) without frequency weighting functions for the auditory experiment [18]. The impact sounds ranging from 20 Hz to 20 kHz were recorded at the sampling frequency of 44100 Hz.

Heavy-weight floor impact sounds generated by the rubber ball could be classified into three groups (A-C) according to their spectral characteristics [25]. A higher number of heavy-weight floor impact sounds were classified into spectral Group B than into the other two groups, according to previous studies [18,25]. Among the heavy-weight floor impact sounds classified into spectral group B (see Fig. 1), the real rubber ball sound was selected as representative of the group's averaged characteristics for the auditory experiment. Acoustic stimuli were created by manipulating the recorded rubber ball sound. Fig. 1 shows impact sound pressure levels of the selected rubber ball sound, plotted against four-octave bands frequencies ranging from 63 Hz to 500 Hz. L_{max} of the original rubber ball sound was 87.5 dB, and the background noise level was approximately 39.3 dB. In particular, the sound levels of the background noise at low-frequencies from 63 Hz to 500 Hz were below 26.9 dB. The recorded sound was attenuated, so that the background noise may not be heard at low levels.

Fig. 1

3.1.2. Experimental design

Two factors affecting subjective annoyance caused by heavy-weight floor impact sounds were taken into account: noise levels and DR, temporal decay rates of impact sounds. The maximum SPL with A-weighted frequency response and fast time constant ($L_{A,Fmax}$) was used as a single number quantity for heavy-weight floor impact sounds instead of the inverse A-weighted impact SPL ($L_{i,Fmax,AW}$), because it was found in previous studies [25,26] that $L_{A,Fmax}$ is not only a more practical indicator with respect to the measurement and calculation procedure, but also an indicator that exhibits higher correlation with subjective annoyance caused by rubber ball sounds than $L_{i,Fmax,AW.}$. As shown in Fig 2., DR is defined as the absolute values of the slopes of the linear regression lines of the normalized Schroeder decay curves of impact sounds without any frequency weighting from -5 dB to -35 dB [18]. While the calculation procedure for the DR is similar to that of reverberation time (T30) for room impulse responses, the temporal pattern of floor impact sounds can be affected by not only the sound field characteristics of rooms, such as reverberation time (RT), but also the structural characteristics of the floor and building, such as damping and sound transmission of structural-bone sound [27,28]. In addition, relative to RT, DR (dB/s) more appropriately indicates the temporal decay of impact sounds, which is critical in this study focused on noise annoyance due to perceived impact sound loudness with respect to temporal characteristics. Thus, the temporal decay rate (DR) was used in this study to quantify the temporal characteristics of floor impact sounds.

A total of 28 floor impact sounds were created based on a 2 (DR) × 14 ($L_{A,Fmax}$) factorial design. Using the raw recorded rubber ball sound, two reference floor impact sounds with 30 dB/s and 60 dB/s DR were created; these DR values were chosen because more than 70% of the ball sound DRs ranged from 30 dB/s to 60 dB/s. The just noticeable difference in DR for the rubber ball sounds was approximately 11 dB/s [18]. The DR of acoustic stimuli was manipulated according to Eq. (2).

$$y' = ye^{-nt} \qquad (2)$$

where n is a positive number, t is the delay time from the initial time point, and y and y' are the amplitudes of the original and modified sound source samples, respectively. $L_{A,Fmax}$ of the 30 dB/s and 60dB/s DR reference acoustic stimuli were then varied from 34 dB to 73 dB, in intervals of 3 dBA, to create the final set of acoustic stimuli. All subjects were presented with a few practice sounds before the actual experiments were performed. The acoustic stimuli were presented to the subjects at random to avoid sequential bias. Stimuli consisted of five events of 2-s-long floor impact sounds; thus, each stimulus lasted 10 seconds. Stimuli were separated by 5-s-long intervals during which the subjects rated their annoyance.

The subjects were asked to assess noise annoyance caused by floor impact sounds by using a 7-points Likert scale (0: not at all, 1: insignificantly, 2: somewhat, 3: moderately, 4: considerably, 5: highly, 6: extremely) and 7 statement scales that were developed in Section 2. A Likert scale is a psychometric scale that measures how much respondents agree or disagree with a particular statement. Likert scales assume that attitude distances on each item are equal [29]. The subjects were presented with the following question: "How much would you be annoyed if you were exposed to this noise in the living room?" In addition, individual noise sensitivities of the participants were evaluated by using 20 items describing the participants' attitude and feelings toward noise; these items were used in the previous study [22,30].

Fig. 2

3.1.3. Procedure

Overall, 60 subjects (42 males and 18 females), who have lived in multi-story apartment buildings and have been exposed to floor impact sounds, participated in the auditory experiment for evaluating the floor impact sounds. The participants were aged 22 to 42 (mean age = 25.4, standard deviation = 3.5). Forty-one subjects who took part in Experiment I (82%) also made their estimations using both the scales in Experiment II. Before starting the experiment, the subjects were tested for their hearing threshold levels by using an audiometer (Rion AA-77), and all subjects were reported to have normal hearing.

Experiment II was conducted in a testing booth with background noise of 25 dBA. Because floor impact sounds have significant characteristics in low frequency range, reproducing the stimuli by using only headphones was not suitable for the auditory experiment. Thus, the acoustic stimuli were presented by using open-type headphones (Sennheiser HD-650) and subwoofers (Velodyne DD-10), for sufficiently reproducing floor impact sounds in low frequency range (< 63 Hz), similar to the previous studies [17,18].

3.2. Results

3.2.1 Annoyance test

Fig. 3 shows the mean annoyance ratings of the floor impact sounds as a function of $L_{A,Fmax}$, for two different DRs. In general, subjective annoyance ratings increased with increasing $L_{A,Fmax}$ of stimuli. Annoyance ratings were significantly correlated with $L_{A,Fmax}$ at the level of 0.01. Correlation coefficients between annoyance and SPL for the floor impact sounds were 0.81 and 0.84 for DRs of 30 dB/s and 60 dB/s, respectively. Mean difference between annoyance ratings for different DRs was examined by conducting a t-test, and significant mean differences with respect to DRs were found at the level of 0.01. The floor impact sounds for DR = 30 dB/s were rated as more annoying than those for DR = 60 dB/s. This result supports the conclusions of the previous study [18] stating that DRs significantly contribute to the perceived annoyance of floor impact sounds.

Fig. 3

3.2.2 Classification of heavy-weight floor impact sounds

Percentages of annoyed subjects, denoted by %A, who rated ‘3: moderately’ or higher on the 7-point scale were calculated and corresponded to the 50% dissatisfaction reported in the previous study. Fig. 4 shows %A as a function of $L_{A,Fmax}$, for different DRs. There is a significant difference between %A obtained for different DRs. Even though same impact sound levels were presented to the subjects, rapidly decaying floor impact sounds were perceived to be less annoying than slowly decaying sounds.

Fig. 4

Probit regression analysis was performed to fit the measured data for DRs, as shown in Fig. 4. Probit regression analysis, a type of regression that analyzes binomial response variables, transforms the S-shaped dose-response curve to a linear line that can be analyzed by regression through maximum likelihood [31]. All the probit regression curves showed good correlations with the measured data, showing correlation coefficients of more than 0.98. The relationship between the impact noise level and %A in the 20%–80% range of the regression line by probit analysis was considered to be indicative of a linear relationship [15,32] as in the following linear equations Eq. (3-5). The slopes of these regression equations were about 3.7% per dBA, in good agreement with the previous study [32]:

$$\%A_{DR30} = 3.69\ L_{A,Fmax} - 135.3\ (R^2 = 0.97,\ p<0.01) \qquad (3)$$

$$\%A_{DR60} = 3.74\ L_{A,Fmax} - 158.9\ (R^2 = 0.98,\ p<0.01) \qquad (4)$$

$$\%A_{overall} = 3.79\ L_{A,Fmax} - 150.8\ (R^2 = 0.99,\ p<0.01) \qquad (5)$$

Classifications of heavy-weight floor impact sounds in terms of DRs based on the dose-response curves of %A were proposed as shown in Table 3. Heavy-weight floor impact levels were classified into four groups with 20% interval of %A, so that five classes were proposed as listed in Table 3. For each class, $L_{A,Fmax}$ of the floor impact sound corresponded to the percentage of annoyed subjects obtained within the laboratory experiment. Class I indicates good acoustic condition, in which less than 20% of the subjects evaluated the stimuli as annoying, while Class V denotes the condition in which more than 80% of the subjects rated the stimuli as annoying or highly annoying, representing the worst acoustic condition in terms of annoyance. The difference between $L_{A,Fmax}$ values for DRs of 30 dB/s and 60 dB/s was approximately 5 dBA for each class.

Table 3

Fig. 5 shows mean statement scale values obtained based on the selected statements, as a function of the impact noise level. Correlation coefficients between the scale values and SPL for the floor impact sounds with DRs of 30 dB/s and 60 dB/s were 0.80 and 0.82, respectively, and were statistically significant at the level of 0.01. Similar to the annoyance evaluations performed by using the 7-point verbal scale, significant mean difference of scale values for different DRs was observed. The mean scale values ranged from 1.26 to 4.97 depending on the impact noise levels, and were relatively smaller than those obtained by using the 7-point scale.

The classification based on the dose-response curve of annoyance evaluated by the Likert scale has the limitation that it cannot provide perceptual information on acoustic quality in residential buildings to laypersons. The developed EAI scales are useful in classifying annoyance levels of floor impact sounds by using various expressions describing the attitude of laypersons toward noise in daily life. Even though the Likert scale and EAI scale assume that the distances from each item are almost equal, the items covered in the two scales do not exactly correspond to each other. Therefore, to determine the appropriate statements describing the classification of heavy-weight floor impact noise, the range of the EAI scale values were selected based on the boundary noise levels for %A classification. Example statements relating to the %A classification are listed in Table 4. Using this matching between the statement scales and the classification, the levels of classifications can be explained by attitudes towards noise in living environments. For instance, the scale values of the statements corresponding to Class I ranged from 0.6 to 2.3. Based on the statements classified into Class I, acoustic environments in Class I can be described as quiet. The scale values for Class II statements ranged from 2.3 to 2.9 and included the statements describing acoustic environments in which the residents just recognized the floor impact noise without being annoyed. It can be said that the residents started to consider floor impact sounds as noise only for sounds in Class III. In the case of Class IV, floor impact sounds could be heard clearly and disturbed the residents. The statements indicating the worst acoustic environments were classified into Class V.

Fig. 5

Table 4

4. Discussion

4.1 Acceptable noise levels for floor impact sounds

Five levels of classification for heavy-weight floor impact sounds were suggested based on the subjective annoyance responses in this study. Each classification level can be interpreted based on the corresponding statements toward noise attitudes in residential buildings. Acceptable noise limits of impact sounds in indoor environments for day and night periods are 57 dBA and 52 dBA of $L_{A,Fmax}$ (1 min), respectively [14]. The classification in this study supports the noise regulation in residential buildings by providing empirical evidence; the acceptable limits for day and night periods correspond to Class IV and III, respectively (see Table 3). As shown in Table 4, Class III (%A: 40% - 60%) indicates the perceived noise level at which the residents started to consider floor impact sounds as noise, and Class IV (%A: 60% - 80%) represents annoying indoor acoustic environments due to floor impact sounds.

4.2 Effect of floor impact sound's decay rate on the classification

Significant differences between annoyance ratings were found for different DRs. A two-way analysis of variance (ANOVA) was performed for examining the effect of DRs and noise levels on noise annoyance, and the results are summarized in Table 5. The main effects of DRs and noise levels were statistically significant ($p<0.01$). Even though the contributions of DR and $L_{A,Fmax}$ to noise annoyance were 27% and 73%, respectively, showing a good agreement with a previous study [18], the interaction between DR and $L_{A,Fmax}$ was found to be significant, in contrast to the previous study. This discrepancy might be caused by the different noise annoyance evaluation methods; Kim et al. [18] adopted paired comparison methods by using nine floor impact sounds, while the Likert scale was used in the present study. Paired comparison method is useful for clearly discriminating the subjects' perception, whereas the variance of subjective evaluations based on the rating scales is relatively larger than that obtained by using the paired comparison method, owing to the difference between response ranges for humans.

Using only two levels of DR in the auditory experiment might be a limitation in examining the relationship between noise annoyance and DR of heavy-weight floor impact sounds. Even though the effect of DR on noise annoyance was smaller than that of $L_{A,Fmax}$, future studies should explore the relationship between annoyance and DR with greater precision to suggest a correction model for classifying heavy-weight floor impact sounds that compensates for the effect of DR.

Table 5

4.3 Influence of noise sensitivity on the classification

Noise sensitivity is one of the critical non-acoustic factors affecting subjective evaluation of noise annoyance. Owing to the individual noise sensitivity, annoyance responses of residents to same noise-level floor impact sounds are different [22]. To examine the effects of noise sensitivity on the classification of heavy-weight floor impact sounds, the subjects in Experiment II were divided into three groups (HS: high sensitivity, NS: normal sensitivity, LS: low sensitivity), according to the division used in the previous study [20]. The numbers of subjects belonging to the high, normal, and low sensitivity groups were 12 (20%), 36 (60%), and 12 (20%).

Percentage of annoyed subjects is plotted in Fig. 6 as a function of $L_{A,Fmax}$, for different noise sensitivity groups. The probit regression curves for noise sensitivity groups were highly correlated with the measured data, showing correlation coefficients of more than 0.95. It was found that %A differences between high and normal sensitivity groups were not significant, whereas those between high and low sensitivity groups were significant. It is interesting to note that the differences between high and low sensitivity groups increased with increasing impact noise level. This finding indicates that the effect of noise sensitivity on annoyance is more significant for higher levels of floor impact sounds.

Classification of heavy-weight floor impact sounds according to noise sensitivity is shown in Fig. 7. The inter-class differences between noise sensitivity groups increase with increasing $L_{A,Fmax}$; the $L_{A,Fmax}$ ranges for Class I and Class II exhibit relatively smaller differences among noise sensitivity groups, while the ranges for Class III and Class IV exhibited significant difference between high and low noise sensitivity groups. In particular, the ranges of $L_{A,Fmax}$ in Class IV for high and low sensitivity groups did not overlap at all. This implies that when impact sounds at 58 dBA are generated, the residents with high noise sensitivity are likely to perceive the acoustic environment as Class V, whereas those with low noise sensitivity may evaluate the acoustic quality as Class IV. This demonstrates that the residents' perception and responses to noise might be inconsistent, depending on their individual noise sensitivity, particularly when heavy-weight floor impact sound levels range from 50 dBA to 60 dBA. This implies that acceptable noise levels should be approximately 50 dBA for avoiding the effects of noise sensitivity. In this context, classifications accounting for noise sensitivity will provide useful information for solving noise disputes arising between residents with different noise sensitivity.

Despite these findings, dose-response relationships in this study are limited to the laboratory conditions, which capture real dwellings only to a limited extent and concentrate on short-term effects of noise. Additional studies, based on surveys, are therefore necessary for investigating long-term effects of floor impact noise. In addition, it should be noted that the developed EAI scale with statements is constructed based on Korean situations; thus, it has somewhat limited applicability to other studies performed in countries with different cultural background.

Fig. 6

Fig. 7

5. Conclusions

An equal-appearing interval scale using statements describing attitudes and impressions related to floor impact sounds was developed. Annoyance levels for heavy-weight floor impact sounds were evaluated for different DRs and $L_{A,Fmax}$ by using both the Likert scale and the developed equal-appearing interval statement scale by conducting auditory experiments. Classifications of heavy-weight floor impact sounds based on the annoyance tests were proposed and the statements corresponding to each class successfully explained the acoustic comfort in dwellings. It was found that annoyance increased with decreasing temporal decay rate of impact sounds. DRs also significantly influenced classification of floor impact sounds, with a classification difference of approximately 5 dBA for DRs of 60 dB/s and DR 30 dB/s. This finding supports the notion that temporal decay rate of a sound critically affects the evaluation of impact sounds. It was also revealed that noise sensitivity also significantly affected the classification. As sound levels of impact sounds increased, the high sensitivity group evaluated the impact sounds as more annoying compared with the low sensitivity group. This difference in annoyance responses among noise sensitivity groups was clearly observed in the 50 dBA to 60 dBA ranges, potentially explaining noise disputes between dwellers. Recently, the acoustic classification scheme for dwellings using the rubber ball method has been discussed in ISO/TC 43/SC 2 WI 19488 [33]. The findings of this study can provide useful knowledge for evaluating the perception of floor impact sounds in residential buildings. In addition, the classification approach adopted in this study by using both the rating scale and the EAI scales based on statements can be applied to other sources of indoor noise in residential buildings.

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[33] ISO/TC43/SC2 N1244 Voting results ISO-NP 19488. Acoustic classification scheme for dwellings. Geneva, Switzerland: International Standard Organization.2014.

Table 1 Medians and interquartile ranges of 33 collected sentences (IQR: interquartile range)

No.	Median	IQR	Statement
1	0.6	1.91	The indoor environment is quiet.
2	1.0	1.88	It is as if there is no one living upstairs.
3	1.1	1.86	Noise cannot be heard.
4	1.1	2.19	We live a pleasant life.
5	1.2	2.48	It is possible to concentrate on things.
6	1.2	2.06	I can take a nap.
7	1.4	2.34	Noise does not bother me.
8	1.5	2.91	I do not worry about floor-to-floor noise.
9	2.0	4.50	It is possible to live without being aware of the upstairs neighbors
10	2.2	2.37	If you have patience, noise problems can be handled.
11	2.4	1.83	In any case, there are no complaints.
12	2.5	3.47	The movements of the upstairs neighbors can be felt.
13	2.6	1.93	It is possible to read indoors.
14	2.8	1.43	We can live with the noise.
15	2.8	1.70	If I concentrate, I can hear the noise.
16	2.9	3.15	I am sometimes aware of my upstairs neighbors.
17	3.0	3.12	We need to be considerate about each other.
18	3.1	2.57	It is okay if the upstairs neighbors provide us with compensation.
19	3.3	1.66	I am frequently aware of my upstairs neighbors.
20	3.5	4.36	The noise from upstairs can be heard clearly.
21	4.0	1.77	Noise disturbs my relaxation time.
22	4.5	2.33	The noise wakes up a child who begins crying.
23	4.5	2.44	I consider moving to another apartment.
24	4.5	1.68	Indoor conversation cannot be heard due to noise from upstairs neighbors.
25	4.6	1.54	Noise stresses me out.
26	4.6	1.70	I may file a complaint about the noise.
27	4.6	2.42	I have growing disdain for my upstairs neighbors due to the noise they generate.
28	4.7	0.82	It is not possible to read indoors.
29	4.7	1.63	I go upstairs to complain to the neighbors.
30	4.9	1.69	I seriously contemplate soundproofing my home.
31	4.9	1.38	I get angry because of the noise.
32	4.9	1.69	It is possible that I will get into an argument with the neighbors.
33	5.3	2.11	It is impossible for people to live here.

Table 2 Seven selected statements based on floor impact sound.

Class	**Scale value**	**Statement**
A	0.6	The indoor environment is quiet.
B	1.4	Noise does not bother me.
C	2.2	If you have patience, noise problems can be handled.
D	3.0	We need to be considerate about each other.
E	3.9	Noise disturbs my relaxation time.
F	4.5	Indoor conversation cannot be heard due to noise from upstairs neighbors.
G	5.3	It is impossible for people to live here.

Table 3 Classification of heavy-weight floor impact sounds in terms of DRs.

Class	%A	$L_{A,Fmax}$ [dBA]		
		DR30	DR60	Overall
I	0 – 20%	$<$ 42.0	$<$ 47.0	$<$ 44.5
II	20 – 40%	$<$ 47.5	$<$ 52.5	$<$ 50.0
III	40 – 60%	$<$ 52.5	$<$ 57.5	$<$ 55.0
IV	60 – 80%	$<$ 58.0	$<$ 62.0	$<$ 60.0
V	80 – 100%	$\geq$ 58.0	$\geq$ 62.0	$\geq$ 60.0

Table 4 Classification of the statements describing attitudes toward floor impact sounds.

Class	$L_{A,Fmax}$ [dBA]	Scale value	Statements
I	34.0 – 44.5	0.6	The indoor environment is quiet.
		1.0	It is as if there is no one living upstairs.
		1.1	Noise cannot be heard.
		1.2	I can take a nap.
		1.4	It does not bother me.
		1.5	I do not worry about floor-to-floor noise.
		2.0	It is possible to live without being aware of the upstairs neighbors.
		2.2	If you have patience, do not mind about noise.
II	44.5 – 50.0	2.4	In any case, there are no complaints.
		2.5	The movements of the upstairs neighbors can be felt.
		2.6	It is possible to read indoors.
		2.9	I am sometimes aware of my upstairs neighbors.
III	50.0 – 55.0	3.0	We need to be considerate about each other.
		3.1	It is okay if the upstairs neighbors provide us with compensation.
IV	55.0 – 60.0	3.3	I am frequently aware of my upstairs neighbors.
		3.5	The noise from upstairs can be heard clearly.
		4.0	Noise disturbs my relaxation time.
V	60.0 – 73.0	4.5	Indoor conversation cannot be heard due to noise from upstairs neighbors.
		4.6	Noise stresses me out.
		4.7	It is not possible to read indoors.
		4.9	I get angry because of the noise.
		5.3	It is impossible for people to live here.

Table 5 Summary of two-way ANOVA for annoyance with the DR and $L_{A,Fmax}$ factors.

Factor	Sum of squares	Degrees of freedom	Mean Square	F	p-value
DR	76.90	1	76.90	104.44	0.00
$L_{A,Fmax}$	2641.89	13	203.22	276.00	0.00
Interaction	20.92	13	1.61	2.19	0.01
Residual error	1200.17	1630	0.736		
Total	3932.67	1657			

Figure captions

Fig. 1 Frequency responses of measured rubber ball sounds classified into spectral group B. The bold line indicates the spectral characteristics of the rubber ball sound selected for the auditory experiments.

Fig. 2 Temporal decay rates of the stimuli.

Fig. 3 Mean annoyance ratings as a function of SPL. Error bars indicate the standard deviations.

Fig. 4 Percentage of annoyed subjects as a function of $L_{A,Fmax}$, for different DRs.

Fig. 5 Mean statement scale values as a function of $L_{A,Fmax}$. Error bars indicate the standard deviations.

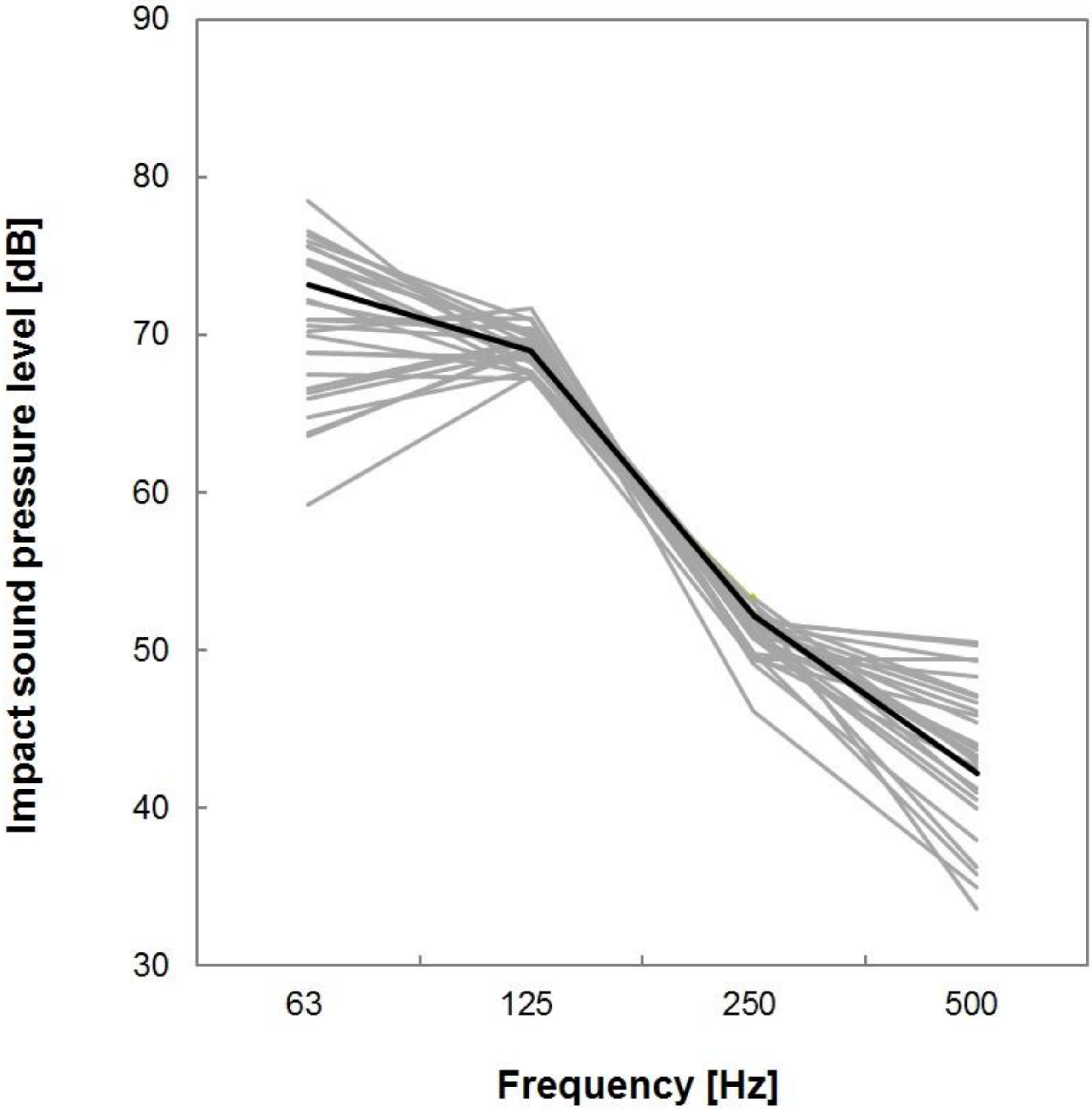
Fig. 6 Percentage of annoyed subjects as a function of $L_{A,Fmax}$, for different noise sensitivity groups (HS: high sensitivity, NS: normal sensitivity, LS: low sensitivity).

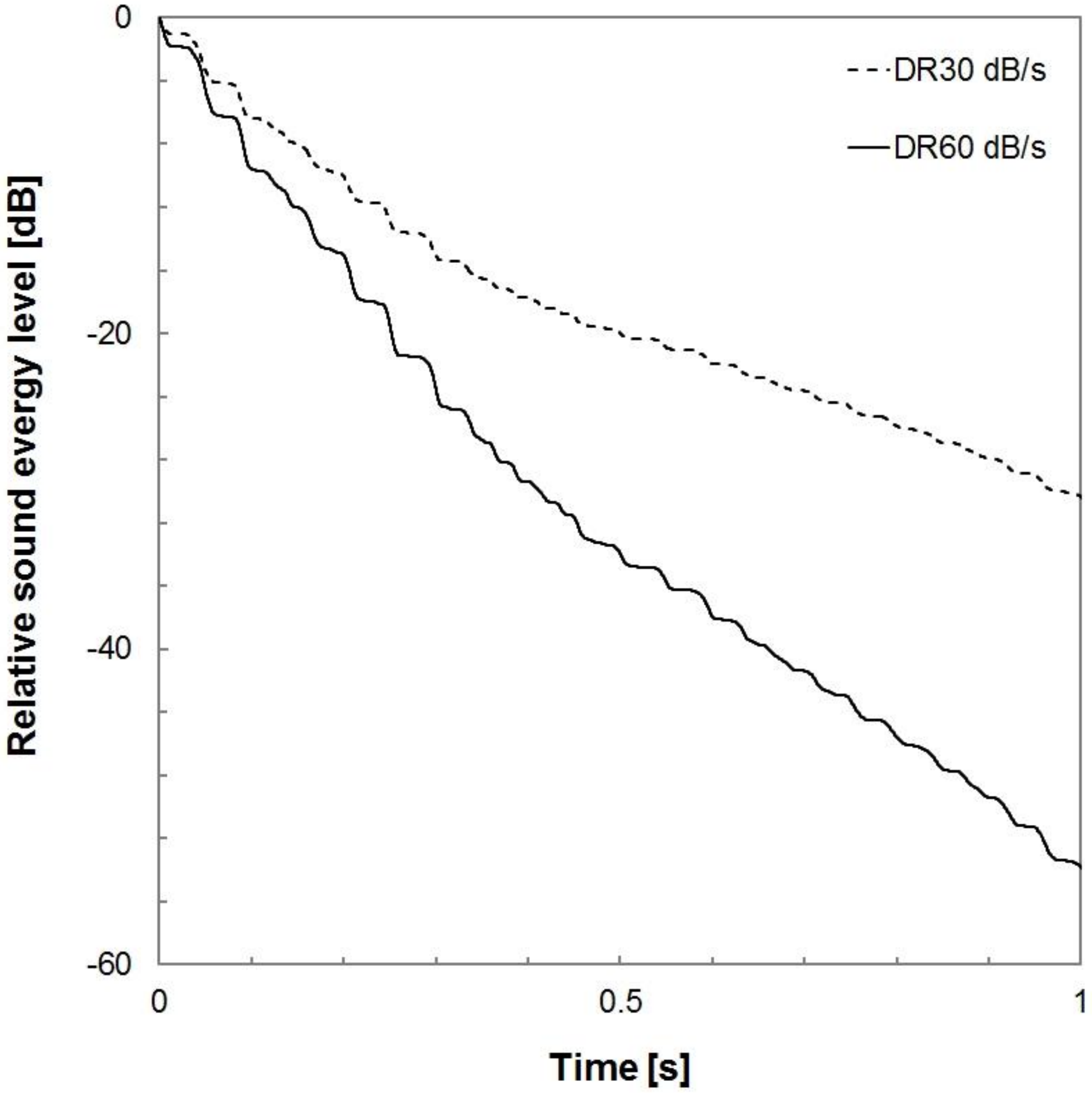
Fig. 7 Classification of floor impact sounds for different noise sensitivity groups (HS: high sensitivity, NS: normal sensitivity, LS: low sensitivity).

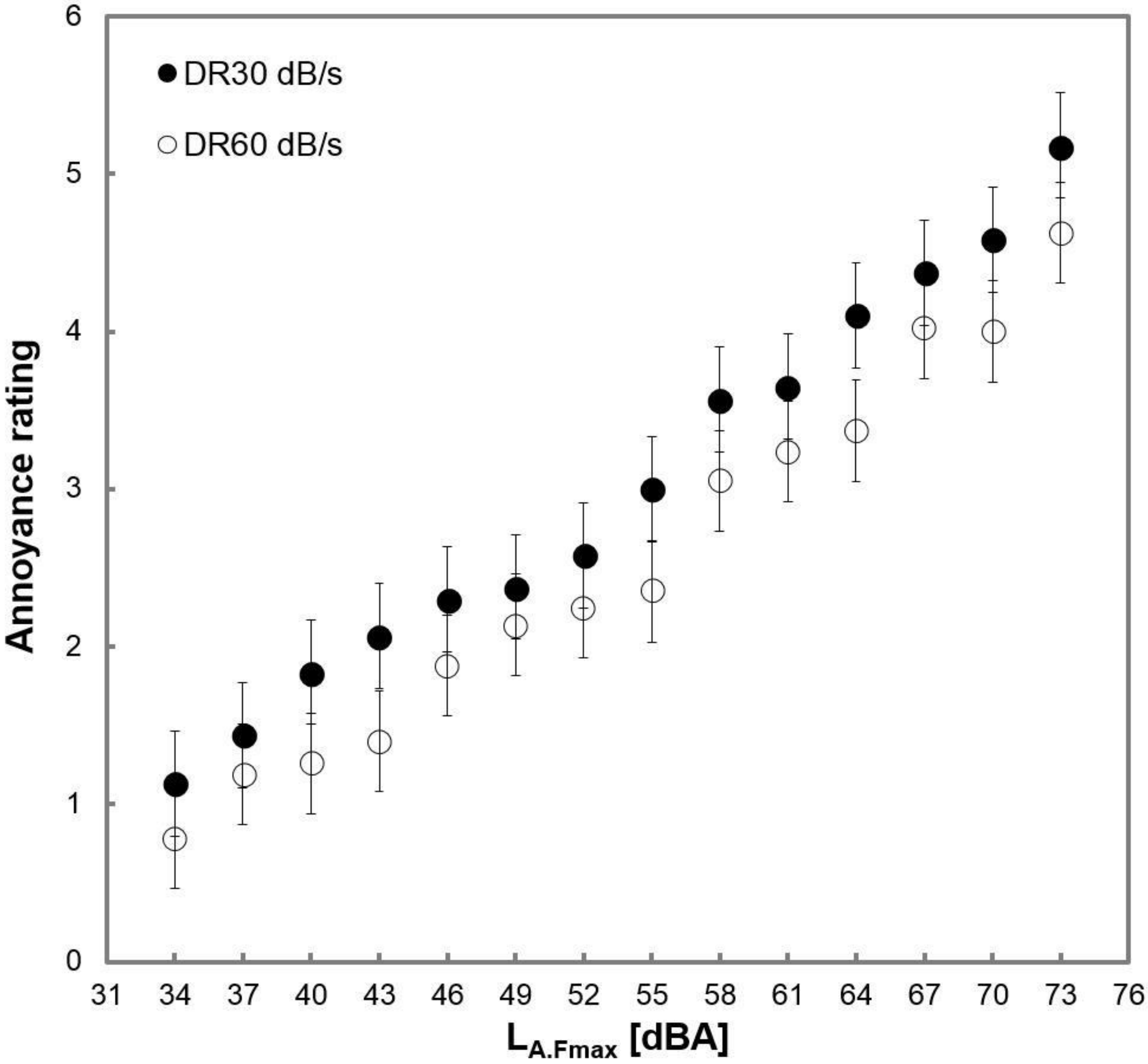
Appendix

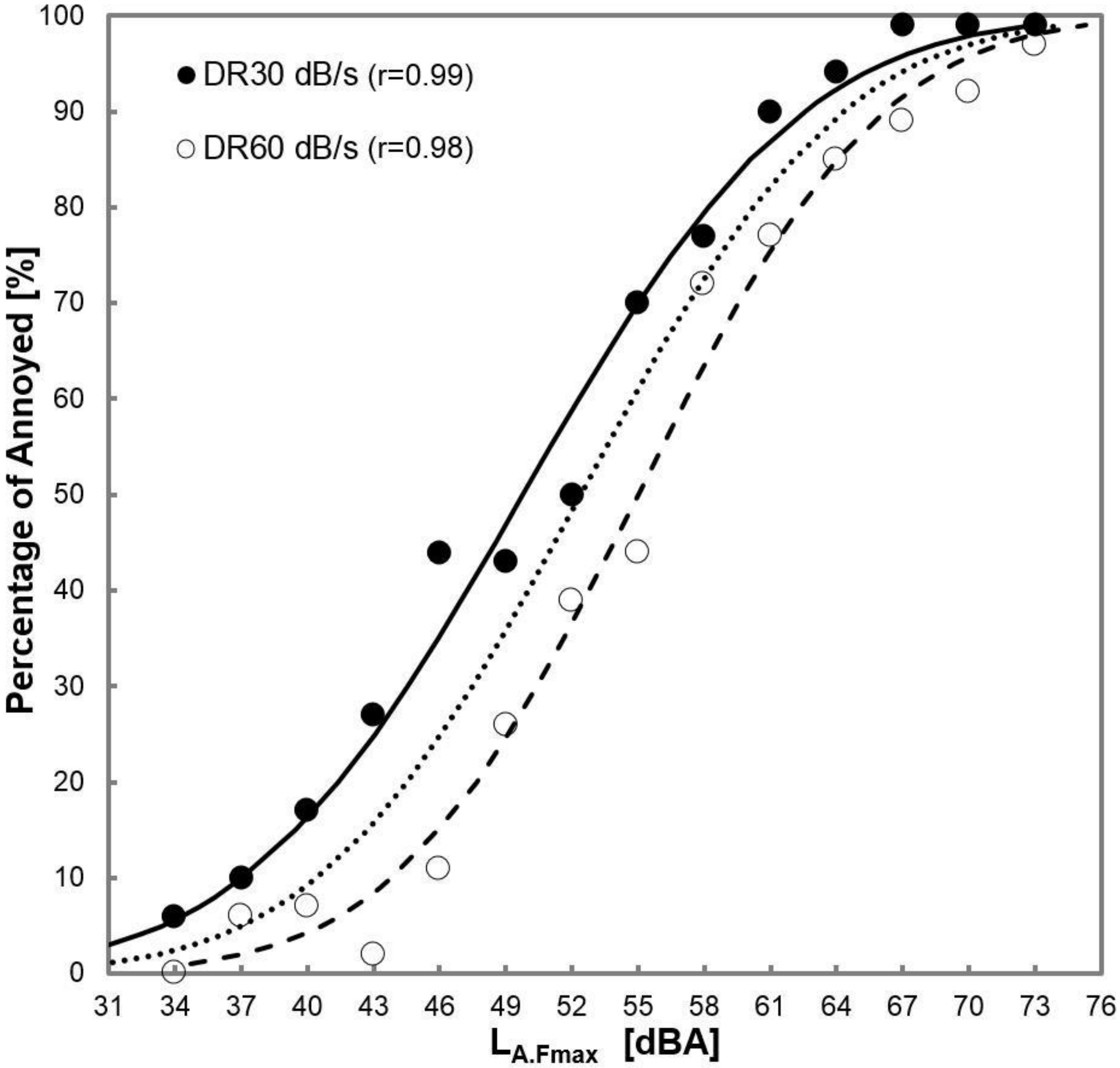
Questionnaire for noise sensitivity

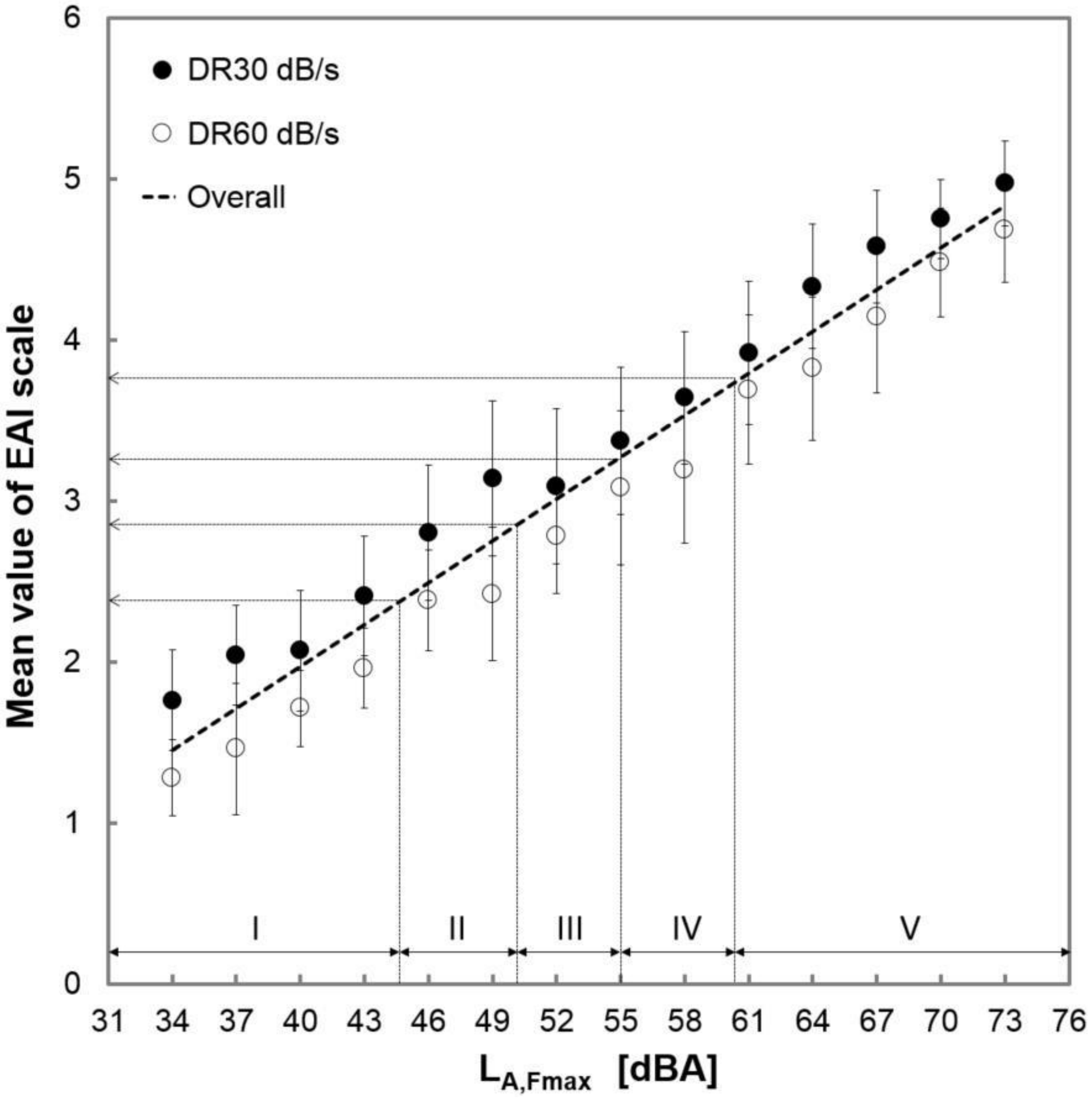
Questions
I am uneasy when I hear noise.
I often desire a quiet environment.
I complain once I have run out of patience with a noise.
I am annoyed even by low noise levels.
I cannot concentrate well in noisy surroundings.
I get mad when I hear loud music.
Noise disturbs my concentration when reading a newspaper.
When I hear a noise, I picture the source (acts) in my head.
I cannot fall asleep easily because of the noise.
I would not want to live on a noisy street, even if the house/apartment was nice.
I would not like to live across the street from a fire station.
Even music I normally like will bother me if I am trying to concentrate.
I find it hard to relax in a noisy place.
I worry that my neighbor can hear noise coming from my apartment.
I would not want to live in a house with poor noise insulation.
I am easily awakened by noise.
Noise during a meal makes me uncomfortable.
There are often times when I want complete silence.
I am confused by noise.
I often experience headaches and/or digestive disorders due to noise.


Impact sound pressure level [dB]
90
80
70
60
50
40
30
63
125
250
500
Frequency [Hz]

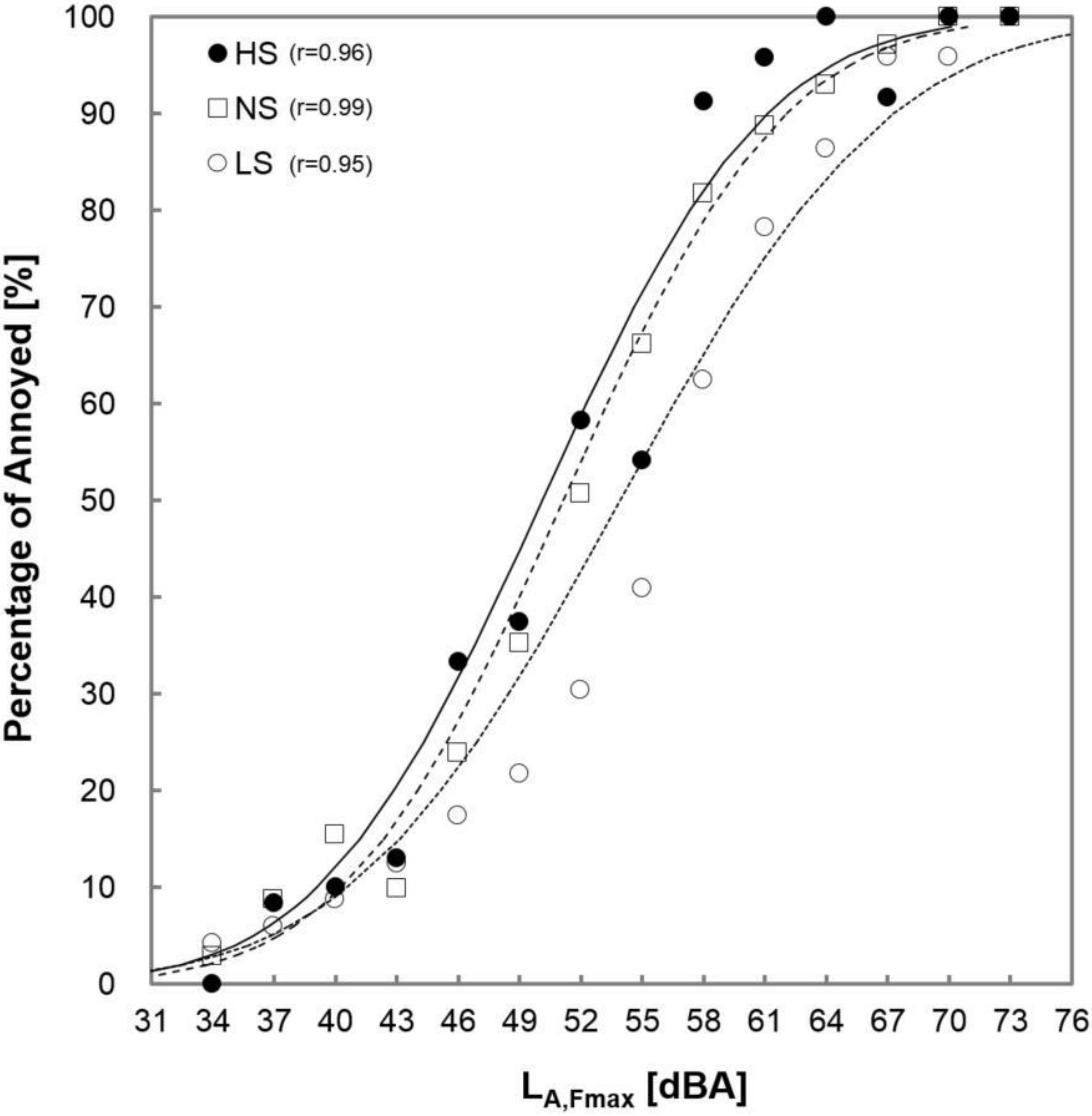

0
-20
-40
-60
Relative sound evergy level [dB]
0
0.5
1
Time [s]
DR30 dB/s
DR60 dB/s

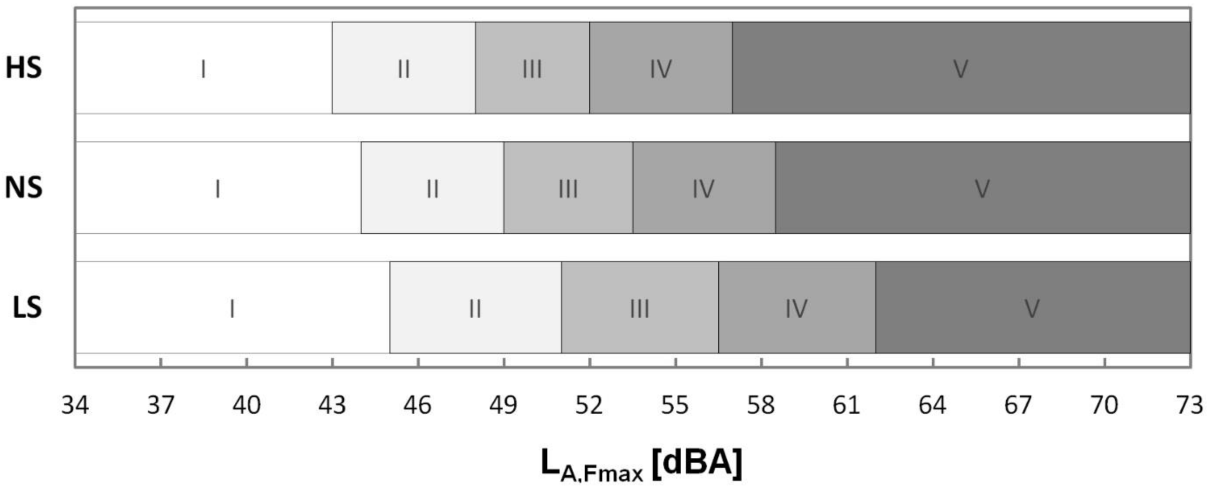

● DR30 dB/s
○ DR60 dB/s
Annoyance rating
0
1
2
3
4
5
6
31
34
37
40
43
46
49
52
55
58
61
64
67
70
73
76
$L_{A.Fmax}$ [dBA]


● DR30 dB/s (r=0.99)
○ DR60 dB/s (r=0.98)
Percentage of Annoyed [%]
$L_{A.Fmax}$ [dBA]
0
10
20
30
40
50
60
70
80
90
100
31
34
37
40
43
46
49
52
55
58
61
64
67
70
73
76



DR30 dB/s
DR60 dB/s
Overall
Mean value of EAI scale
0
1
2
3
4
5
6
I
II
III
IV
V
31
34
37
40
43
46
49
52
55
58
61
64
67
70
73
76
L_{A,Fmax} [dBA]


HS (r=0.96)
NS (r=0.99)
LS (r=0.95)
Percentage of Annoyed [%]
0
10
20
30
40
50
60
70
80
90
100
31
34
37
40
43
46
49
52
55
58
61
64
67
70
73
76
$L_{A,Fmax}$ [dBA]


HS
NS
LS
I
II
III
IV
V
34
37
40
43
46
49
52
55
58
61
64
67
70
73
$L_{A,Fmax}$ [dBA]