ACTA ACUSTICA UNITED WITH ACUSTICA
Vol. 105 (2019) 5 – 8
DOI 10.3813/AAA.919280

Single-Number Quantities of Heavyweight Impact Sound Insulation

Jeong Ho Jeong[1], Sang Hee Park[2], Pyoung Jik Lee[2]
[1] Fire Safety & Building Environment System Research Team, Fire Insurers Laboratories of Korea, Yeoju-si, Gyeonggi-do, South Korea
[2] Acoustics Research Unit, School of Architecture, University of Liverpool, Liverpool, UK. P.J.Lee@liverpool.ac.uk

Summary
This study aims to determine which single-number quantities (SNQs) of heavyweight impact sounds are the most appropriate for explaining subjective response. Two hundred and eleven participants participated in the listening experiment in Korea (Experiment I) to assess heavyweight impact sounds generated by a rubber ball and an adult jumping in heavyweight and lightweight buildings. A small-scale listening test (Experiment II) was then performed in the UK to validate Experiment I with 43 European participants. For all the sounds with different sound sources and building types, $L_{i\mathrm{A,Fmax}}$ was the best SNQ although other predictors also showed relatively high correlation coefficients with annoyance ratings. Experiment II confirmed the findings of Experiment I, implying that $L_{i\mathrm{A,Fmax}}$ is the most effective SNQ across ethnicity.

1. Introduction

A number of studies have dealt with the relationship between single-number quantities (SNQs) and the subjective ratings for lightweight impact sounds generated by tapping machines and human walking [1, 2, 3]. Based on their efforts, the SNQs for lightweight impact sounds have been widely developed [3, 4, 5] beyond an international standard [6]. Compared to the lightweight impact sounds, only a limited number of studies have examined heavyweight impact sounds produced by standard and real impact sources. Japan and Korea have used several SNQs of the heavyweight impact sounds using a reference curve [7, 8]. However, recent studies [8, 9] pointed out that the use of a reference curve is not superior to other conventional quantities for explaining people's reaction to heavyweight impact sounds.

The main purpose of this study is to examine SNQs for assessing heavyweight impact sounds in heavyweight and lightweight buildings. The first laboratory experiment was conducted with a large number of Korean participants to investigate the relationship between SNQs and noise annoyance. European participants were then invited to the second experiment to validate the results of the first experiment.

2. Methods

2.1. Stimuli

The sound stimuli were recordings of floor impact sounds in heavyweight and lightweight buildings using a head and torso simulator (Brüel & Kjær Type 4100). All the recordings were conducted at night to secure a low, background noise level (< 35 dBA) and reverberation time of the room was also controlled using panel absorbers to have 0.5 s at 1 kHz. The floor impact sounds were generated using standard and real impact sources. For heavyweight buildings, a heavy/soft impact source (hereinafter 'rubber ball') was used [9]. The sound of an adult jumping on the floor (hereinafter 'jumping') was used along with rubber ball for lightweight buildings. Among the recordings, 16 and 30 sound stimuli were chosen for heavyweight and lightweight buildings, respectively. The sound pressure levels of the stimuli in Korea (hereinafter 'Experiment I') randomly ranged from 25 dB to 70 dB in terms of $L_{i\mathrm{A,Fmax}}$ (A-weighted maximum impact sound level). In the experiment conducted in the UK (hereinafter 'Experiment II'), the range of the sound pressure level was quite similar to that of Experiment I, but was adjusted in 5 dB steps for heavyweight buildings and 10 dB steps for lightweight buildings. For both experiments, the duration of the stimuli, which consisted of four repeated sounds with an inter-stimulus interval of 2 s, was about 10 s. Each stimulus was presented with an interval of 10 s.

Received 10 October 2018,
accepted 6 December 2018,

2.2. Procedure

In Experiment I, the participants were recruited separately for two sessions (heavyweight and lightweight buildings) in order to minimise the effect of fatigue on subjective ratings. One hundred and one participants took part in the session for heavyweight buildings, while 110 participants attended the session for lightweight buildings. Experiment II was conducted with 43 adults (60% British and 40% from other parts of Europe). A training session was conducted before starting the sessions, in order to help the participants become acquainted with the experiment. In particular, the participants were instructed to imagine that they were seating in the living room to minimise the perceptual difference between the laboratory and real world. During the main sessions, the stimuli were randomly presented to avoid order effects. After each noise exposure, the participants were asked to rate their annoyance using a 7-point scale (0 = '*Not at all*' to 6 = '*Extremely*'). Experiment I was conducted in a soundproof room with low background noise level and short reverberation time. The sound stimuli were presented through two subwoofers and five loudspeakers. The subwoofers were placed in front of the participants and the loudspeakers were mounted 1.2 m above the floor to simulate noise from upstairs. Experiment II was carried out in an anechoic chamber with a loudspeaker and a subwoofer. The subwoofer was placed on the floor behind the participants, while the loudspeaker was placed 2 m above the floor.

2.3. Single-number quantities (SNQs)

In this study, a total of seven SNQs were introduced. The three SNQs in KS F 2863-2 were $L_{i,\mathrm{Fmax,Aw}}$ (inverse A-weighted impact sound pressure level), $L_{i\mathrm{A,Fmax}}$, and $L_{i\mathrm{Avg,Fmax(63-500)}}$ (arithmetic average of maximum sound pressure level in octave bands from 63 Hz to 500 Hz). Also $L_{i,\mathrm{Fmax,r}}$ in JIS A 1419-2 was used in this study. Both $L_{i,\mathrm{Fmax,Aw}}$ and $L_{i,\mathrm{Fmax,r}}$ are computed by comparing each sound pressure level from 63 to 500 Hz with the inverse A-weighting contour. In addition, Zwicker's Loudness Level (LL_Z), N_{max} (maximum loudness), and N_5 (loudness exceeded in 5% of loudness) were also considered.

3. Results

3.1. Experiment I

Figure 1 shows the mean annoyance ratings for heavyweight impact sounds as functions of $L_{i\mathrm{A,Fmax}}$. Simple linear regressions were plotted to describe the relationship between annoyance ratings and sound pressure level. As expected, the noise annoyance ratings increased with increasing noise level for all noise sources and building types. The mean annoyance ratings were below '1' on a 7-pt scale when $L_{i\mathrm{A,Fmax}}$ was lower than 30 dB because the floor impact noise is rarely noticeable at very low noise level [10]. For the rubber ball sounds, the general behaviour in heavyweight buildings was similar to that in lightweight buildings. However, when compared with jumping, the regression line for the rubber ball sounds in lightweight buildings was almost identical to that for jumping. These results indicate that the contribution of sound pressure level to noise annoyance is more dominant than those of source and buildings type. The correlation coefficients between annoyance ratings and SNQs were calculated and listed in Table Ia. All the SNQs showed considerably high correlation coefficients above 0.9 across different sources and building types. In particular, sound energy based SNQs showed higher coefficients than loudness based SNQs.

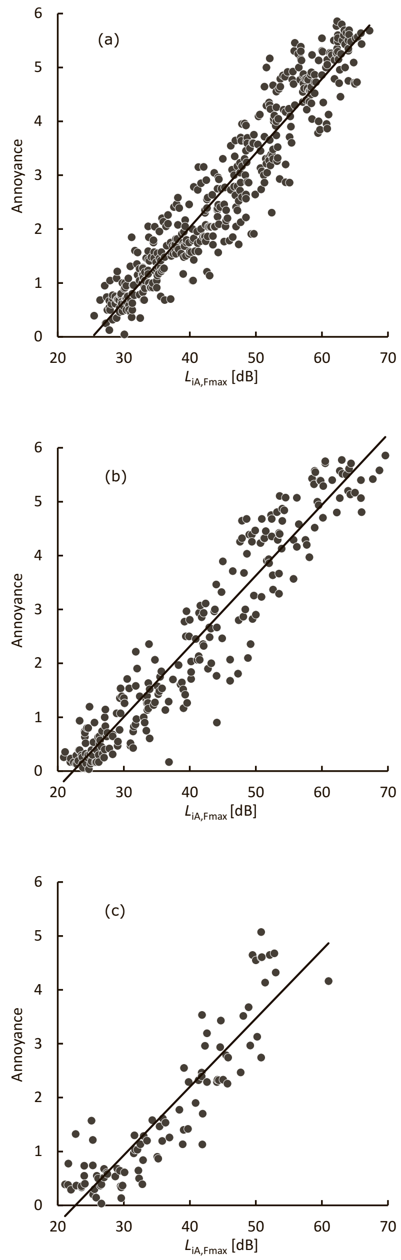

Figure 1. Relationships between mean annoyance ratings and $L_{i\mathrm{A,Fmax}}$ for Experiment I; (a) rubber ball in heavyweight building, (b) rubber ball in lightweight building, and (c) jumping in lightweight building. The solid line in each panel indicates linear regression of the data points shown.

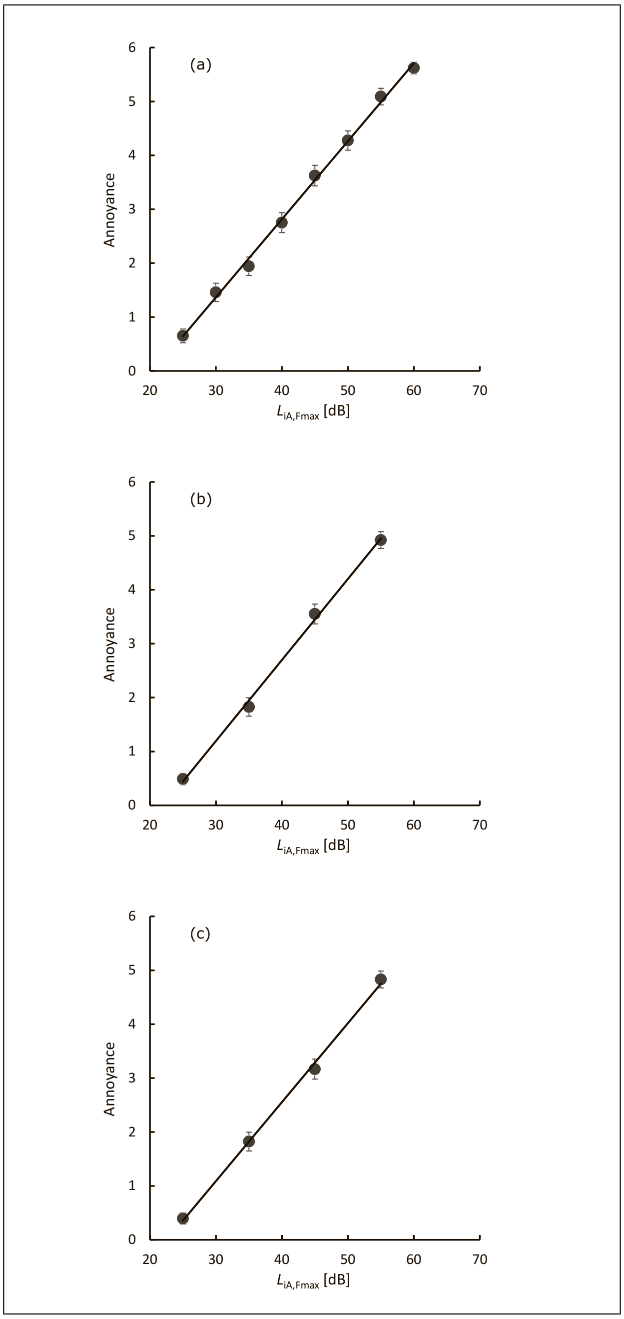

Figure 2. Relationships between mean annoyance ratings and $L_{i\mathrm{A,Fmax}}$ for Experiment II; (a) rubber ball in heavyweight building, (b) rubber ball in lightweight building, and (c) jumping in lightweight building. The solid line in each panel indicates linear regression of the data points shown. The error bars indicate standard errors.

3.2. Experiment II

Similar to the Experiment I, the mean annoyance ratings increased along with $L_{i\mathrm{A,Fmax}}$ (Figure 2). For lightweight buildings, the annoyance ratings of the rubber ball and jumping were similar, and the differences between them were not statistically significant. It was also found that the annoyance ratings of rubber ball sounds in heavyweight and lightweight buildings were not significantly different. The similarity in annoyance ratings for different building types might be because the sound stimuli showed similar spectral characteristics. The correlation coefficients between annoyance ratings and SNQs for Experiment II (Table Ib) confirmed the results of Experiment I. All the SNQs showed very high correlation coefficients with annoyance ratings across different sound stimuli. The correlation coefficients were consistent across different types of sound stimuli. $L_{i\mathrm{A,Fmax}}$ showed the highest correlation coefficients for three sound stimuli, while the coefficients of N_{max} or N_5 were the lowest.

Table I. Correlation coefficients between single-number quantities and annoyance ratings. $p < 0.01$ for all values. Rub_H: Rubber ball, Heavyweight building, Rub_L: Rubber ball, Lightweight building, Jump_L: Jumping, Lightweight building.

	Rub_H	Rub_L	Jump_L
a) Experiment I			
$L_{i,\mathrm{Fmax,Aw}}$	.949	.939	.845
$L_{i,\mathrm{Fmax,r}}$	.929	.924	.834
$L_{i\mathrm{A,Fmax}}$	.953	.939	.848
$L_{i\mathrm{Avg,Fmax(63-500)}}$	.963	.950	.849
LL_Z	.947	.930	.905
N_{max}	.881	.858	.868
N_5	.887	.856	.859
b) Experiment II			
$L_{i,\mathrm{Fmax,Aw}}$	.983	.974	.989
$L_{i,\mathrm{Fmax,r}}$	.976	.972	.973
$L_{i\mathrm{A,Fmax}}$	.986	.990	.992
$L_{i\mathrm{Avg,Fmax(63-500)}}$	.974	.965	.991
LL_Z	.974	.987	.988
N_{max}	.865	.931	.937
N_5	.856	.927	.939

4. Discussion

The results of this study are consistent with the findings of previous studies [11, 12], in which there were high correlation coefficients between the SNQs and subjective responses. Lee *et al.* [12] used nine rubber ball impact sounds recorded in heavyweight buildings with constant noise levels of 50 dB ($L_{i,\mathrm{Fmax,Aw}}$). High correlation coefficients above 0.88 were consistently found across sound stimuli with different spectral characteristics. LL_Z showed the highest correlation coefficients, followed by $L_{i\mathrm{A,Fmax}}$ and N_{max}. Ryu *et al.* [11] conducted two separate experiments with rubber ball impact sounds from wooden structures. In the first experiment with a narrow sound level range between 45 and 65 dB ($L_{i\mathrm{A,Fmax}}$), N_5 showed the highest correlation coefficient, while the other SNQs showed similar coefficients. In the next experiment, spectral adjustments were made for all frequency bands when the sound pressure levels were fixed at 55 and 65 dB. For the sound stimuli at 55 dB, $L_{i\mathrm{Avg,Fmax(63-500)}}$ showed much higher correlation coefficients than the other SNQs based on the reference curve. This is mainly because sound energy at 63 Hz and higher octave bands without A-weighting were considered in the calculation of $L_{i\mathrm{Avg,Fmax}(63-500)}$. However, the correlation coefficients were quite similar for the sound stimuli at 65 dB, although the highest correlation coefficient was shown by $L_{i\mathrm{A,Fmax}}$. The previous studies evaluated the appropriateness of the SNQs mainly in terms of the correlation coefficient; however, it was not reported if there were statistically significant differences between the correlation coefficients. On the other hand, the present study tested the significance of differences between coefficients using Fisher's r-to-z transformation [13]. In both Experiment I and Experiment II, the sound energy based SNQs showed significantly higher correlation coefficients than loudness based SNQs, except for LL_Z with rubber ball sounds ($p < 0.05$ for all). In Experiment II, the correlation coefficients of $L_{i\mathrm{A,Fmax}}$ were significantly higher than those of others for the impact ball sounds ($p < 0.05$ for all). These results imply that sound energy based SNQs are better than loudness based SNQs for explaining the participants' experiences. In particular, $L_{i\mathrm{A,Fmax}}$ might have advantages as an SNQ because it does not require frequency analysis or the use of a reference curve. Therefore, $L_{i\mathrm{A,Fmax}}$ can be recommended as a practical SNQ on the basis of its ease of measurement and calculation process.

5. Conclusion

This study investigated the relationship between single-number quantities (SNQs) of heavyweight impact sounds and noise annoyance. A total of seven different SNQs were calculated for standard and real impact sources in heavyweight and lightweight buildings. The results of the large-scale listening test with 211 Korean participants showed significant correlations between the SNQs and annoyance across different impact sources and building types. Most SNQs showed relatively similar correlation coefficients with subjective ratings. Therefore, among the SNQs, $L_{i\mathrm{A,Fmax}}$ was chosen as the most appropriate one due to practical reasons. Similar results were found in an additional small-scale listening test with 43 Europeans, which showed high correlation coefficients between the SNQs and subjective ratings. The findings of this study may contribute to the development of an international standard on the objective rating of heavyweight sound insulation.

Supplementary material

The file 'v105n01_jeong_park_lee_supplementary_files.zip', containing supplementary material can be downloaded via http://aaua-material.com/t_HF7755

References

[1] D. Olynyk, T. Northwood: Assessment of footstep noise through wood?joist and concrete floors. J Acoust Soc Am. **43** (1968) 730–733.

[2] M. Kylliäinen, J. Lietzén, V. Kovalainen, V. Hongisto: Correlation between single-number-quantities of impact sound insulation and various noise ratings of walking on concrete floors. Acta Acust united Ac. **101** (2015) 975–985.

[3] M. Kylliäinen, V. Hongisto, D. Oliva, L. Rekola: Subjective and objective rating of impact sound insulation of a concrete floor with various coverings. Acta Acust united Ac. **103** (2017) 236–251.

[4] F. Ljunggren, C. Simmons, K. Hagberg: Correlation between sound insulation and occupants' perception – Proposal of alternative single number rating of impact sound. Appl Acoust. **85** (2014) 57–68.

[5] K. G. Hagberg: Evaluating field measurements of impact sound. Building Acoustics **17** (2010) 105–128.

[6] ISO 717-2: Acoustics – Rating of sound insulation in buildings and of building elements – Part 2: Impact sound insulation. International Standard Organization, Geneva, Switzerland, 2013.

[7] JIS A1419-2: Acoustics – Rating of sound insulation in buildings and of building elements – Floor impact sound insulation. Japanese Industrial Standards Committee, Tokyo, Japan, 2000.

[8] KS F 2863-2: Rating of floor impact sound insulation for impact source in buildings and of building elements – Part 2: Floor impact sound insulation against standard heavy impact source. Korean Standards Committee, Seoul, Korea, 2007.

[9] ISO 10140-5: Acoustics – Laboratory measurement of sound insulation of building elements – Part 5: Requirements for test facilities and equipment. International Standard Organization, Geneva, Switzerland, 2010.

[10] S. H. Park, P. J. Lee: Effects of floor impact noise on psychophysiological responses. Build Environ. **116** (2017) 173–181.

[11] J. Ryu, H. Sato, K. Kurakata, A. Hiramitsu, M. Tanaka, T. Hirota: Relation between annoyance and single-number quantities for rating heavy-weight floor impact sound insulation in wooden houses. J Acoust Soc Am. **129** (2011) 3047–3055.

[12] P. J. Lee, J. H. Kim, J. Y. Jeon: Psychoacoustical characteristics of impact ball sounds on concrete floors. Acta Acust united Ac. **95** (2009) 707–717.

[13] J. H. Steiger: Tests for comparing elements of a correlation matrix. Psychol Bull. **87** (1980) 245.