Levels and sources of neighbour noise in heavyweight residential buildings in Korea

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Abstract

Indoor noise level is a significant factor for occupants' health, comfort, and psychological well-being in residential buildings; hence the World Health Organization (WHO) recommends guidelines for residential buildings based on the 24-hour sound levels. However, only few studies have examined 24-hour noise levels and sources from neighbours. Consequently, 24-hour noise measurement is necessary for understanding noise level and acoustic comfort in homes. Field measurements were performed in 26 residential apartments in Korea to investigate levels and types of noise from neighbours. Noise recordings were carried out at each residence in unoccupied conditions. The recordings were analysed at 1 minute intervals in terms of the A-weighted equivalent (L_{Aeq}) and maximum sound pressure levels (L_{AFmax}) for three different time periods during the day. It was found that 20 apartments met the recommended WHO guidelines during the daytime (07:00–23:00). However, at night (23:00–07:00), eight apartments were in excess of the WHO guideline value in terms of L_{Aeq} while L_{AFmax} exceeded the WHO limit level in 21 apartments during the night. Human footsteps, movement of furniture, and dropping of small items were found to be major sources accounting for approximately 80% of all the noise events. L_{AFmax} of children's jumping and dropping small items were greater than others. Adults' walking showed larger variation of noise levels than other sources. Moreover, it was found that indoor noise levels were not affected by slab thickness and major noise sources.

Keywords: indoor environment, neighbour noise, noise level, noise source, residential building

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1 Introduction

Noise has been considered as a threat to public health and well-being [1]. Several studies have reported that chronic exposure to noise can cause annoyance, sleep disturbance, and health problems. Miedema [2] argued the significant effect of transportation noise on the prevalence of noise annoyance. It has been known that noise has not only auditory health effects (e.g., hearing loss, noise-induced hair-cell damage) but also various non-auditory health risks such as daytime sleepiness or it can impair cognitive performance in schoolchildren [3, 4]. It was also reported that aircraft and road traffic noise has a high impact on cardiovascular health (e.g., high blood pressure, ischemic heart diseases) [5].

However, the majority of work has mainly focused on environmental noise such as road traffic noise and railway noise. In contrast, few studies have investigated the impact of neighbour noise on residents' psychophysiological well-being. Maschke *et al.* [6] conducted a cross-national questionnaire surveys in eight European cities and found that annoyance caused by neighbour noise increased health risks in the cardio-vascular system. But noise exposure level at home is unknown because they did not perform noise measurement. Pujol *et al.* [7] investigated children's exposure to noise at home in an urban area by measuring long-term indoor noise levels at homes. They were mainly concerned with noise from outside rather than indoor noise sources, and noise sources were not identified during the measurements [7]. Therefore, it is still unknown which indoor noise sources contribute to noise levels in residential buildings.

In order to examine the health effects of environmental noise exposure, 24-hour noise measurements have commonly been conducted [8, 9]. Several noise descriptors such as day-night level (DNL) and day-evening-night level (DENL) have been introduced to describe overall noise exposure for 24 hours. Noise measurements for 24 hours or working hours have also been occasionally performed in non-residential buildings such as hospitals and offices

[10, 11]. On the other hand, very little data exists describing 24-hour noise exposure and most previous studies on residential buildings measured only short-term indoor noise levels. Jeon *et al.* [12] measured noise levels while the apartment was empty and the windows were closed. Lai *et al.* [13] measured the noise levels for 15 minutes in 32 residential apartments and the average noise levels for 15 minutes were found to be 67.1 dBA with a variation from 52 to 77.9 dBA. Noise levels for one hour were also measured in urban residential buildings under a natural ventilation condition [14]. Similarly, Pujol *et al.* [7] measured the noise levels in bedrooms and the main rooms to analyse children's exposure to environmental noise at home. They found the averages of noise levels for day, evening, and night in 44 dwellings were 51.3, 53.6, and 36.9 dBA, respectively. However, short-term field measurements only represent a snapshot condition of an indoor built environment at a specific time. In addition, the World Health Organization (WHO) recommends guidelines for residential buildings in terms of the average sound levels for 16 hours (daytime) and eight hours (night) [1]. Therefore, 24-hour noise measurement in residential buildings is required to improve our understanding of noise level and acoustic comfort at homes.

The majority of dwelling types in South Korea are multi-story and heavyweight (i.e. reinforced concrete) apartment buildings [15]. In multi-story buildings, residents are easily exposed to a number of noises from their neighbours, thus a large number of complaints regarding dwelling noise have been raised by apartment residents [15]. In order to resolve noise problems in apartment buildings, multi-layered floor structures, consisting of a concrete slab, resilient isolator, lightweight concrete, and finishing mortar, have been used. In addition, the Korean Government strengthened the domestic regulations in 2005 and 2007 by increasing the concrete slab thickness to 180 mm and 210 mm, respectively [16] because the slab thickness of the apartments mostly ranged between 135 mm and 150 mm before 2005. Empirical studies [17, 18] supported the decision of the Korean Government reporting that the impact sound insulation of the floors had improved with the increases of the concrete slab thickness. According to Jeong *et al*. [18], a 30 mm increase of slab thickness led to an increase of heavyweight impact sound insulation of 2 dB. However, contrary to expectations, the complaints of neighbours' noises have still increased; number of complaints about floor impact sound recorded in the Ministry of Environment of Korean Government increased from 114 in 2005 to 341 in 2010. However, the complaints were also raised from residents living in old apartments built before 2005, so it is still unknown whether or not increased slab thickness is effective in reducing indoor noise levels in real buildings.

The present study aims to determine noise levels and noise sources from neighbours in residential buildings. It is hypothesised that noise levels are influenced by noise sources and that indoor noise levels are hypothesised to be affected by slab thickness. To validate these hypotheses, 24-hour noise measurements were conducted in the living rooms of 26 residential apartments. During the measurements, the apartments were empty and windows were closed to minimise the influence of outdoor noise on indoor noise levels. The recording were analysed in terms of the equivalent and maximum noise levels (L_{Aeq} and L_{AFmax}, respectively) based on three time periods of the day: day (07:00–19:00), evening (19:00–23:00), and night (23:00–07:00). Furthermore, noise sources from neighbours were identified by listening to the recordings and the levels of each noise source were analysed.

2 Method

2.1 Sites

Twenty six reinforced concrete apartments were selected for the 24-hour noise recordings. Of these, 15 were in Seoul and others were located in cities nearby Seoul. As listed in Table I, the net floor areas of the apartments ranged from 42.0 to 212.5 m^2. The number of bedrooms in each home varied from two to five. The house age also varied; the oldest apartment was built 32 years ago and the latest one was just 3 years old. Slab thicknesses of the apartment buildings varied from 135 mm to 210 mm; the apartments built before the domestic regulation was strengthened in 2005 had slab thickness of 135 mm and 150 mm. Sizes of groups were quite similar; 14 sites were classified into Group 1, while Group 2 had 12 sites. This distinction was made because the Korean Government introduced a domestic regulation requiring construction companies to increase the concrete floor slab thickness by 30 mm at that time. Most homes under measurement were away from traffic roads, which provides a relatively consistent environmental noise condition.

Table 1

2.2 Procedure

Noise levels in living rooms were measured under unoccupied conditions from the morning to the following morning for 24-hour periods while the residents were vacated. The windows in the living rooms and balconies of all the homes were closed during the measurements to minimise the effects of outdoor noise. All the windows were double glazed and the balconies were adjacent to the living rooms at all sites; thus, it was expected that the influence of outdoor noise on indoor noise levels is limited. The measurements were performed only during weekdays to avoid influences of neighbour’s daily activities on the recordings. The noise was recorded using a half-inch free field microphone (B&K Type 4189) positioned at a sitting position in the living rooms. The microphone was directly connected to the noise monitoring system (DUO, 01dB) which has the calibrated recording feature as all-in-one device. The noise levels were monitored continuously for 24 hours and noise was recorded whenever the noise level exceeded 30 dBA (L_{Aeq}) at a sample rate of 51.2 kHz. The recordings were then transferred to a laptop computer. Before the data collection, the entire measurement system was calibrated using an acoustic calibrator (B&K Type 4280).

2.3 Data analysis

One-minute interval noise level data were exported from the noise monitoring system (DUO, 01dB). The data were then processed using dBTrait software from 01dBmetravib. According to the WHO guidelines [1], all noise events for 1 minute, and 2) A-weighted maximum sound pressure level (L_{AFmax}) of the noise event. The L_{AFmax} was calculated using the 'fast' time constant for analyses of the recorded noises. The WHO guideline recommends the noise levels for daytime (07:00–23:00) and night time (23:00–07:00); however, in the present study, 24-hour period is classified into the day (07:00–19:00), evening (19:00–23:00), and night (23:00–07:00) according to ISO 1996-2 [19].

In order to identify the noise source, the occurrence of the noise events was defined as an event exceeding the WHO recommended values for day and night noise in dwellings. During the daytime, the recommended values are 35 dBA (L_{Aeq}), while the values for the night are 30 dBA (L_{Aeq}) and 45 dBA (L_{AFmax}). The present study also set the threshold L_{AFmax} value for the daytime as 50 dBA, which is adopted from the domestic guidelines of the Korean Government. Firstly, the noise levels exceeding the recommended value were identified based on the one-minute interval noise level data. Secondly, the noise sources and lengths of the noise events were then manually recognised by listening to small sections of the recordings and visually observing time histories as an interval of 125 ms. All airborne and structure-borne noise events were identified; of structure-borne noise sources, heavyweight and lightweight impact sources were also recognised through repetitive manual listening. Several sources were identified based on objective characteristics. For example, adults' walking and children's running were recognised mainly based on step frequency (speed of footstep) and interval between the steps. In addition, other noise sources before and after the footsteps were considered because children's running were usually accompanied by other activities such as playing with toys. Each noise source had a different length; therefore, the noise levels of each source were converted into an A-weighted sound exposure level (L_{AE}), which is the equivalent sound level during the event normalised to a period of one second.

3 Results

3.1 Noise levels

Table 2 lists percentage, median, minimum, and maximum values of $L_{Aeq,1min}$ and L_{AFmax} for the 24 hours, day, evening, and night. The data of this study were non-normally distributed (p = 0.05, the Shapiro–Wilk test); therefore, the presentation of median values were used throughout the current paper since they are helpful for describing data which is not normally distributed. The median values for L_{Aeq} for 24 hours, day, and evening were quite similar and slightly greater than 30 dBA, whereas that of night was less than 30 dBA. It was found that the variation in the noise levels was greatest in the evening followed by night and day. All the outliers above the 5% percentiles were due to loud announcements from the public address (PA) system installed in each home. The median of the L_{AFmax} for 24 hours was the greatest, followed by day, evening and night. The boxplot of the L_{AFmax} for 24 hours shows the highest median value as it contains all the data of L_{AFmax} for whole day. The medians for 24 hours and day were greater than 60 dBA, whereas the median of night was less than 50 dBA. The variation in noise levels at night was much shorter than other periods. For the $L_{Aeq,1min}$, most levels were below 40 dBA, and only less than 1% exceeded 40 dBA. Contrary to the L_{Aeq}, the percentage of the L_{AFmax} exceeding 40 dBA significantly increased.

The levels between 30 dBA and 40 dBA showed the highest percentages, and more than 20% of the levels were greater than 40 dBA in the daytime and evening.

Table 2

3.2 Noise sources

Noise sources and their number of occurrences from 26 apartments are listed in Table 3. Mean and standard deviation are also listed to show how many times each source is heard from each apartment. The noise sources were classified into airborne and structure-borne sound sources according to the sound transmission methods [17]. Five sources were airborne, and these were public address (PA) system, domestic equipment, voice, and other sounds such as musical instruments. It was found that a total of 77 occurrences were produced by airborne sound sources, and the number of occurrences of children's voice was the largest. Similarly, the structure-borne sound source had nine sub-sources such as footsteps and movement of furniture. The number of noise events due to the structure-borne sound sources was 495, which accounts for 86.5% of all noise events. This shows that structure-borne noise sources are dominant in residential apartments. The number of occurrences for movement of furniture was the largest, followed by dropping small items, children's running, and adults' walking. It was observed that only five noise sources had mean values which are greater than 1. This indicates that other noise sources occurred less than once during a 24-hour period. However, low number of occurrences does not guarantee acoustic comfort in apartments because only noise events exceeding WHO recommended noise levels was counted in the present study. Table 3 included all the noise sources from above and the neighbouring units on the same floor and hallway. The majority of the noise sources were coming from the upstairs. In particular, all the heavyweight and lightweight impact sounds were generated by the residents above except for the door banging. In total, 17 of 41 door banging sounds (41.5%) came from the hallway and the neighbours on the same floor. Therefore, it was assumed that the inside noise levels were dominated by the structure-borne noises from upstairs. However, it was not possible to identify where the airborne sounds came from by listening to the recordings in the present study.

Durations of each noise source are also described in Table 3. The lengths of each noise source are quite different. The length of door banging was very short (median = 3.3 seconds), whereas noise from the plumbing system had a long duration (median = 108.0 seconds). Other sources such as musical instruments were found to have the largest duration. Among the structure-borne noise sources, the longest noise event was children's running at 1683 seconds.

Table 3

Figure 1 shows the number of occurrences for day, evening, and night across noise sources. It was found that the majority of noise events occurred during the daytime. This was mainly because the period of daytime is the longest, and the activities of the neighbours are most active at this time. For instance, movement of furniture, dropping small items, and children's running were dominant in the daytime. The number of occurrences of movements of furniture was the largest during the day, but they were also observed during the evening and night. In particular, the noise events that occurred by movement of furniture consisted of various movements noise events of furniture (e.g., scraping noises of table or chairs, impact noises of chairs etc.) while most of the events at night were shorter impact noises of chairs. The noise from the movement of furniture also lasted two times longer during the day time than night.

Figure 1

Four major noise sources most frequently heard accounting for 75.8% of all noise events were chosen to be investigated: 1) adults' walking, 2) children's running, 3) movement of furniture, and 4) dropping of small items. Figure 2 represents the number of occurrences of four sources across time of day at an interval of one hour. The adults' walking mostly occurred during the daytime, in particular it was the most frequently occurring between 07:00 and 10:00. This maybe because adults' activities are dominant because it is time for getting ready to go to work, helping their children to go to school, or doing household chores. Movement of furniture (e.g., tables and chairs) also occurred frequently during that time which related to people's activities such as having breakfast or doing household chores. In addition, adults' walking was found to most frequently occur at around 13:00–14:00 during which other noise sources (children's running, movement of furniture, and dropping of small items) occurred frequently. It can be said that all of the four noises were closely related at that period, were primarily related to children's activities. In particular, it was identified that children's running noises during the afternoon occurred more frequently with scraping noises of chairs, and dropping or scraping noises of small objects. Movement of furniture had a relatively large number of occurrences in the evening (19:00–20:00) and at night (23:00–00:00). These noise events might be relevant to people's activities when coming back from work, for example, such as having dinner or resting.

Figure 2

Figures 3 and 4 show the boxplots of the noise levels of each noise source in terms of the A-weighted sound exposure level (L_{AE}) and A-weighted maximum noise level (L_{AFmax}), respectively. Large variations of duration for noise sources indicate that L_{Aeq} is not appropriate to describe the noise levels of each source so the presentation of L_{AE} was adopted to describe noise levels of each source. Among the airborne noise sources, the noise from the PA system showed the highest median value in terms of L_{AE} followed by voice of children and other airborne noises. However, as listed in Table 3, the PA system was rarely identified throughout the measurement. Among the structure-borne sources, hammering and door banging produced the highest and lowest medians of L_{AE}, respectively. All the median values of adults' walking, children's jumping, movement of furniture, and dropping small items were similar and children's running and scraping small items had relatively higher median L_{AE} levels. Particularly, these two noise sources had higher median L_{AE} levels than other structure-borne noises (except hammering) since they lasted longer than the others and the time duration is applied to derive L_{AE} level. Children's running lasted 109.4 seconds on average (standard deviation = 263.6, median = 32.0) and the scraping noise of small items lasted 66.1 seconds on average (standard deviation = 76.7, median = 54.0). A similar tendency was observed in the boxplots of L_{AFmax} (Figure 4). The PA system and hammering were the sources producing the highest L_{AFmax} from airborne and structure-borne noise sources but both were barely heard (6 and 4 events in total, respectively). Once the PA system and hammering were excluded, children's jumping and dropping small items were found to be have the higher L_{AFmax} than others followed by children's running and movement of furniture. In addition, airborne noise sources showed larger variations of median values than structure-borne sources.

Figure 3

Figure 4

3.3 Impact of slab thickness and number of noise events for different sources on noise levels

Figure 5 shows the noise levels ($L_{Aeq,24\text{-}h}$, $L_{Aeq,Day}$, $L_{Aeq,Evening}$, and $L_{Aeq,Night}$) across the slab thickness. Contrary to expectations, the noise levels were not much changed with the increases of slab thickness. For example, the medians of $L_{Aeq,24\text{-}h}$ for 135 mm, 150 mm, 180, mm and 210 mm were 30.1, 30.4, 28.2 and 32.9 dBA, respectively. The 26 participating apartments were then classified into two groups according to their slab thickness (Group 1: 16 apartments with slab thicknesses of 135 mm and 150 mm; Group 2: 10 apartments with slab thicknesses of 180 mm and 210 mm) in order to investigate whether the increase in concrete slab thickness led to a reduction of noise events. Since the two sample sizes were unequal, the Mann-Whitney tests were conducted with noise levels (L_{AE} and L_{AFmax}), occurrence number, and length of noise events as dependent variables. The dependent variables only contained the data of structure-borne noises as the grouping factor (thicker slabs) would only affect noise events of structure-borne noises, not airborne noises. The median L_{AFmax} for Group 1 (53.1 dBA) was slightly higher than that of Group 2 (52.4 dBA) and there was no statistical significance found; the medians of L_{AE} for Groups 1 and 2 were 49.0 dBA and 49.1 dBA, respectively. The number of occurrences between Groups 1 and 2 were not significant, whereas Group 2 had significantly longer noise events than Group 1 ($p<0.01$). These results indicate that better sound insulation performance due to increased slab thickness does not guarantee lower noise levels or fewer noise events in real environments because occurrence of neighbour noise is significantly influenced by neighbour's behaviours and activities.

Figure 5

In order to investigate whether indoor noise levels are affected by the number of occurrences and type of noise sources, correlation analyses were conducted. Noise levels (L_{Aeq} and L_{AFmax}) for 24 hours, day, evening, and night were used. Meanwhile, the number of occurrences for all of the sources and number of occurrences for airborne, structure-borne, heavyweight impact, lightweight impact, and four major sources were introduced across different periods (24 hours, day, evening, and night). The analysis was repeated for two groups, who were classified according to their slab thickness. The results of the correlation analysis are listed in Appendix B. Contrary to expectations, L_{Aeq} were not related with the number of occurrences for different types of sources. As shown in Figure 6, this may be due to a couple of the outliers which showed opposite tendencies. For example, Site 1 showed the largest L_{Aeq} with just seven noise events for 24 hours and L_{Aeq} of Site 14 is much lower than mean of 26 apartments although it has most number of noise events. The high noise level from Site 1 was caused by noise from a refrigerator in the kitchen. These results also revealed that indoor noise levels in apartment buildings are mainly influenced by neighbours' behaviours and activities. However, the exclusion of Sites and 1 and 14 resulted in some significant relationships between noise levels and noise sources. Specifically, L_{Aeq} for 24 hours and during the daytime were significantly correlated with the number of occurrences. In contrast, L_{AFmax} had correlations with the number of occurrences for different types of sources. $L_{AFmax,24\text{-}h}$ and $L_{AFmax,Day}$ showed significant relationships with the number of occurrences of all sources, lightweight impact, and four major sources ($r = 0.40$, $r = 0.40$, and $r = 0.39$, respectively; $p < 0.05$ for all). Moreover, $L_{AFmax,Night}$ for the all participated sites and $L_{AFmax,Night}$ of Group 1 were found to have significant correlation with airborne noise ($r = 0.49$ and $r = 0.63$ respectively; $p < 0.05$).

Figure 6

4 Discussions

The results of the overall noise levels showed that 20 of 26 apartments met the recommended daytime L_{Aeq} level of WHO guideline during the daytime. This does not indicate that the noise exposure levels are acceptable because the impact of outdoor noise sources on indoor noise levels was very limited because the windows were closed. The overall noise levels found in the present study had a good agreement with Jeon *et al.* [12] when they measured noise levels at empty apartments with closed windows. However, significant increase of indoor noise levels has been reported when properties are occupied or windows are opened so that outdoor noise is not controlled [7, 12, 13]. The noise levels might have increased if the current measurements were also conducted under natural ventilation conditions. During the night time, the levels of eight of the residential apartments showed an excess of the WHO limit value (30 dBA) in terms of L_{Aeq} for 8 hours. The WHO guideline also recommends that L_{AFmax} should not exceed 45 dBA during the night. It was observed that only four residential apartments showed lower levels than this limit; thus, the residents in 22 apartments might have experienced sleep disturbance at night. Most of the L_{AFmax} at night were produced by movements of furniture between 05:00 and 07:00 or between 23:00 and 00:00. This finding is coincident with a previous study showing that some interviewees complained about noise coming from upstairs early in the morning and late night [20]. It was also found that the noise levels showed large variations across the measured sites. The L_{Aeq} for 24 hours varied from 20.8 to 45.7 dBA, while the difference between the lowest and highest levels of L_{AFmax} was 40.7 dBA in the evening. This indicates that noise levels in apartments are significantly affected by neighbours and their activities.

The present study reported that the dominant noise sources in residential apartments are human walking, movement of furniture, and dropping of small items. This is consistent with the findings of a questionnaire survey on floor impact sound [21] reporting that children's running, dropping of items, and adult's walking were major noise sources. However, surveys in European countries reported quite different findings. A survey in the UK [22] showed that the most annoying neighbouring noise sources were airborne sources such as voices, dogs, and radio/television, whereas the percentage of neighbours footsteps and banging on walls or floors was less than 10%. A survey in the Netherlands also indicated that flushing sounds from a neighbour's toilets were the most commonly heard [23]. It was also found that playing pop music was the most annoying, followed by TV/radio and footsteps. The difference between the present study and the European studies could be attributed to the dwelling types of the respondents. For instance, in the UK study, the majority of the samples lived in semi-detached, detached, or terrace houses, whereas only 13% of them lived in either a flat or a maisonette [22]. A recent study on loudness and annoyance of neighbour noise in residential buildings also reported that subjective ratings varied across housing types [24].

Most studies on auditory experiments have applied the same noise level variations to different noise sources. For example, Jeon *et al.* [25] reported the annoyance ratings of two drainage (i.e., a bathtub draining and a flushed toilet) and two airborne noises (i.e., conversation and piano) with the same noise level variations. Ryu *et al.* [26] also investigated noise annoyance caused by five airborne sources (conversation, piano, ringing telephone, music, and TV). During the experiments, the same noise variation of 30 – 50 dBA was applied to all the noise sources. However, the present study revealed that variations of noise levels were different across noise sources. Therefore, this finding is beneficial for future study, in particular, auditory experiments using neighbour noises.

Previously, improvement of impact sound insulation of the floors has been reported with increases of concrete slabs [17, 18]. However, these measurements were mostly conducted in laboratories using standard impact sources (i.e. impact ball and tapping machine), and noise levels in real situations have not been reported. The present study carried out the Mann-Whitney tests to compare the two groups of apartment with different slab thickness and found no significant difference between them. Therefore, a different approach could be considered to enhance acoustic comfort in apartments. For instance, subjective impression of building noise could be improved by dealing with non-acoustic factors. Recent studies reported a few non-acoustic factors affecting subjective reactions to floor impact noise such as the relationship with neighbours and negative attitude to neighbours as a sound source [27]. It was also reported that residents with higher intimacy with neighbours expressed less noise annoyance than others. This implies that noise annoyance could be reduced by using non-technical factors.

In the present study, 23 of the 26 measurements were conducted in warm seasons (spring, summer, and autumn). Under such conditions, the measured noise levels might be greater than the levels in winter because neighbours' windows are frequently opened. Additionally, 21 of the 26 measurements were performed during the school term so that the noises produced by children's activities were limited. Therefore, additional longitudinal measurements would be necessary in the future to cover all seasons and school holidays. The noise measurements were conducted only in living rooms in this study because noise complaints in living rooms are much more common than in bedrooms [21]. However, approximately 20% of neighbour noise was generated in bedrooms [8]; thus, the measurements in the bedrooms is a topic for future research and practice. Another limitation of this study is the lack of subjective data such as the noise annoyance ratings of the residents. It is quite common to report dose-response functions based on 24-hour noise levels and subjective ratings in the environmental noise fields, but no one has attempted to show the relationship between subjective impressions and 24-hour noise level by highlighting indoor noise, especially noise from neighbours. Therefore, it would be valuable to conduct both field measurements and a questionnaire survey in residential buildings.

5 Conclusion

The present study carried out noise measurements for 24 hours at 26 empty apartments in South Korea. From the measurements, L_{Aeq} and L_{AFmax} for 24 hours, day, evening, and night were analysed. Levels (L_{AE} and L_{AFmax}) and length of identified noise sources were then calculated. Twenty of 26 apartments met the recommended WHO guidelines during the daytime, whereas L_{AFmax} in 21 apartments were in excess of the recommended levels which could potentially cause sleep disturbance. Airborne noise sources included PA systems, domestic equipment, voices of adults, and voices of children. Structure-borne noise sources were more dominant than airborne noise sources, for example human footsteps (adults' walking, children's running and jumping), movement of furniture, dropping or scraping small items, doors banging, plumbing system, and hammering. It was found that adults' walking, children's running, movement of furniture, and dropping of small items were the most frequently occurring, accounting for approximately 80% of all the noise events. Among the airborne noise sources, children's voices were found to have relatively higher noise levels than other sources. Children's jumping was found to have the most severe structure-borne noise source in terms L_{AFmax}. Hammering showed the highest $L_{AE,}$ followed by the scraping of small items and children's running. The present study could not find any statistically significant difference between the apartments with different slab thickness. Moreover, indoor noise levels were affected by neighbours' behaviours and daily activities rather than major noise sources and their number of occurrences. In the future, more preventative measurements, including both lightweight and heavyweight buildings, are required. Measurement of the noise levels in source room would also be useful to better understand noise levels from residents' activities.

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Supporting Information

Appendix A. A-weighted equivalent sound pressure levels ($L_{\mathrm{Aeq,1min}}$) and A-weighted maximum sound pressure levels (L_{AFmax}).

Appendix B. Correlation coefficients between number of occurrence for the noise sources and A-weighted equivalent sound pressure level (L_{Aeq}) for different periods.

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Table 1. Information of apartments at which indoor noise levels were measured.

No.	House age [year]	Floor area [m^2]	Number of bedrooms	Number of floors*	Slab thickness [mm]	Distance from road [m]	Number of lanes per side
1	23	42.0	2	9/17	150	79	2
2	27	62.6	2	1/5	135	80	3
3	10	107.7	3	4/23	180	51	1
4	5	101.5	3	7/11	210	123	4
5	4	131.5	3	14/17	210	61	3
6	11	99.8	3	7/18	180	51	2
7	13	88.0	3	18/22	150	56	1
8	12	151.0	4	3/13	150	25	4
9	16	108.5	3	13/24	150	92	3
10	12	106.9	3	7/16	150	106	4
11	11	107.6	2	11/42	180	41	4
12	13	96.7	3	4/7	150	46	3
13	11	84.9	3	16/19	180	42	1
14	17	84.5	3	4/15	150	29	2
15	17	109.6	3	13/22	150	37	2
16	3	110.1	3	2/13	210	110	3
17	8	126.6	4	20/21	180	171	5
18	11	114.3	3	12/28	150	87	3
19	32	198.1	5	12/15	135	181	2
20	26	97.0	3	8/15	135	35	1
21	18	107.3	3	10/19	150	31	4
22	7	149.1	4	3/12	180	22	1
23	6	212.5	4	32/34	180	75	3
24	24	193.7	5	2/15	150	26	1
25	10	106.2	3	10/29	150	70	3
26	12	110.0	3	9/15	150	33	1
Mean	13.8	115.7	3.2	-	159.8	67.7	2.5
Standard deviation	7.5	38.8	0.5	-	22	42.6	1.2
Minimum	3	42.0	2	-	135	22	1
Maximum	32	212.5	5	-	210	181	5

*The former number is the floor on which the apartment is located; the latter is the total number of the building floors.

Table 2. Percentages, median, minimum, and maximum of one-minute A-weighted equivalent sound levels ($L_{Aeq,1min}$) and A-weighted maximum sound levels (L_{AFmax}).

		Overall 24-h	Day (07:00–19:00)	Evening (19:00–23:00)	Night (23:00–07:00)
$L_{Aeq,1min}$	%≤30 dBA	57.6	54.1	56.3	63.7
	30<%≤40 dBA	42.1	45.6	43.5	36.3
	40<%≤50 dBA	0.2	0.3	0.1	0.1
	%>50 dBA	0	0	0.1	0
	%>threshold		11.1	10.9	36.4
	Median	30.3	30.6	30.1	29.2
	Minimum	20.8	20.2	20.9	19.4
	Maximum	45.7	46.9	48.6	36.2
L_{AFmax}	%≤30 dBA	20.7	13.6	14.7	34.4
	30<%≤40 dBA	63.1	66.2	63.8	58.2
	40<%≤50 dBA	14.6	18.2	19.3	6.8
	%>50 dBA	1.6	2.1	2.2	0.5
	%>threshold		2.1	2.2	2.1
	Median	61	59.7	54.5	49.7
	Minimum	48.8	48.8	45.9	43
	Maximum	87.1	87.1	86.6	70.2

Table 3. Number of occurrence and length of each noise event.

Noise source			Number of occurrence				Length		
			Number	%	Mean	Standard deviation	Median	Minimum	Maximum
Airborne sound source	PA system		11	1.9	0.4	0.9	62.5	43	113.8
	Domestic equipment		2	0.3	0.1	0.4	21.5	18.8	24.3
	Voice	Adults	12	2.1	0.5	1.2	22.8	3	556.8
		Children	37	6.5	1.4	4.5	56	4.5	1020
	Others (e.g., musical instrument)		15	2.6	0.6	1.4	61.8	8.3	428.5
	Sub-total		*77*	*13.5*					
Structure-borne sound source	Heavyweight impact	Adults' walking	65	11.4	2.5	4.1	18.4	1.3	302
		Children's running	82	14.3	3.2	7.4	32	3	1683
		Children's jumping	12	2.1	0.5	1.1	5.4	3	16
	Lightweight impact	Movement of furniture	159	27.8	6.1	8.3	6	1.3	212.5
		Dropping small items	99	17.3	3.8	5.1	5	1.3	82.5
		Door banging	41	7.2	1.6	1.7	3.3	1.5	4.75
		Scraping of small items	16	2.8	0.6	1.3	50.5	5	256.3
		Plumbing system	13	2.3	0.5	1.1	108	45.8	314.5
		Hammering	8	1.4	0.3	1.6	43.4	28.3	110
	Sub-total		*495*	*86.5*					
	Total		*572*	*100*					

Appendix A. Supplementary data: A-weighted equivalent ($L_{Aeq,1min}$) and maximum sound pressure levels (L_{AFmax}).

No.	$L_{Aeq,1min}$ [dBA]				L_{AFmax} [dBA]			
	Overall 24-hour	Day 07.00-19.00	Evening 19.00-23.00	Night 23.00-07.00	Overall 24-hour	Day 07.00-19.00	Evening 19.00-23.00	Night 23.00-07.00
1	45.7	46.9	48.6	34.1	87.1	87.1	86.6	62.4
2	36.0	36.5	35.6	35.4	70.2	68.0	61.3	70.2
3	33.5	33.9	33.9	32.7	62.7	62.7	57.9	52.6
4	30.2	30.5	30.1	29.6	60.0	60.0	51.8	45.8
5	32.9	33.2	33.2	32.3	60.8	60.8	52.4	53.5
6	31.3	32.3	31.1	29.2	73.4	73.4	69.2	49.7
7	32.4	32.7	32.3	32.1	59.4	59.4	50.3	50.0
8	30.0	30.7	29.9	28.9	63.5	63.5	56.2	52.2
9	28.5	29.8	28.2	25.6	57.9	57.9	49.0	56.6
10	20.8	20.2	21.9	20.9	54.0	49.2	54.0	46.1
11	27.9	28.5	27.7	26.8	53.3	53.3	47.1	47.5
12	36.4	36.5	36.2	36.2	65.6	65.6	61.8	62.1
13	24.2	26.3	20.9	19.4	61.2	61.2	49.4	44.5
14	26.6	27.6	28.5	21.7	63.2	58.8	63.2	51.1
15	28.4	28.7	28.1	28.0	57.0	57.0	54.6	46.1
16	34.0	34.0	37.7	29.4	70.4	70.4	70.3	48.5
17	34.5	34.4	34.6	34.6	62.0	62.0	49.7	50.4
18	34.4	36.9	30.1	26.4	74.6	74.6	62.3	53.4
19	30.1	30.4	30.2	29.6	52.4	52.4	49.7	49.7
20	23.7	24.7	24.3	20.9	53.7	52.7	53.7	45.0
21	36.7	30.2	43.7	29.2	74.0	56.6	74.0	45.8
22	23.6	23.9	23.6	23.1	48.8	48.8	47.4	43.0
23	28.2	28.4	28.5	27.7	54.3	53.2	54.3	49.7
24	30.4	31.0	29.6	29.6	63.7	63.7	59.0	48.9
25	31.5	31.8	31.9	30.7	50.0	50.0	45.9	43.7
26	27.8	28.3	28.1	26.7	55.4	54.2	55.4	51.2
Median	30.3	30.6	30.1	29.2	61.0	59.7	54.5	49.7
Mean	30.8	31.1	31.1	28.5	61.9	60.6	57.2	50.8
Minimum	20.8	20.2	20.9	19.4	48.8	48.8	45.9	43.0
Maximum	45.7	46.9	48.6	36.2	87.1	87.1	86.6	70.2

Appendix B. Supplementary data: Correlation coefficients between number of occurrence for the noise sources and A-weighted equivalent (L_{Aeq}) and maximum sound pressure levels (L_{AFmax}) for different periods (*p<0.05). Major four noise sources are adults' walking, children's running, movement of furniture, and dropping of small items.

	Group	Period	Noise sources					
			Total	Airborne	Structure-borne	Heavyweight impact	Lightweight impact	Major four sources
L_{Aeq}	Total	24 hours	.12	.29	.08	.02	.11	.10
		Day	.20	.27	.17	.11	.20	.18
		Evening	.01	.25	-.03	-.05	-.01	-.02
		Night	-.04	.36	-.09	-.14	-.05	-.09
	Group 1	24 hours	.01	.31	-.03	-.06	.00	.01
		Day	.12	.26	.08	.04	.10	.12
		Evening	-.12	.28	-.15	-.14	-.16	-.13
		Night	-.21	.41	-.27	-.28	-.24	-.24
	Group 2	24 hours	.35	.30	.34	.31	.34	.32
		Day	.41	.35	.41	.38	.41	.39
		Evening	.25	.22	.25	.21	.26	.22
		Night	.32	.29	.31	.27	.32	.27
L_{AFmax}	Total	24 hours	.40*	.34	.37	.29	.40*	.39*
		Day	.40*	.30	.37	.28	.40*	.39*
		Evening	.28	.25	.25	.22	.25	.25
		Night	.24	.49*	.18	.12	.21	.19
	Group 1	24 hours	.32	.34	.28	.22	.30	.31
		Day	.33	.26	.30	.23	.33	.33
		Evening	.13	.21	.10	.13	.07	.11
		Night	.15	.63*	.07	.03	.08	.09
	Group 2	24 hours	.57	.38	.59	.51	.60	.61
		Day	.57	.38	.59	.51	.60	.61
		Evening	.54	.36	.56	.47	.58	.56
		Night	.49	.37	.49	.42	.50	.46

Figure captions

Figure 1. Noise sources as a function of number of occurrences.

Figure 2. Number of occurrences of the four most frequent noise sources in hourly interval for 24 hours: (a) adults' walking, (b) children's running, (c) movement of furniture, and (d) dropping of small items.

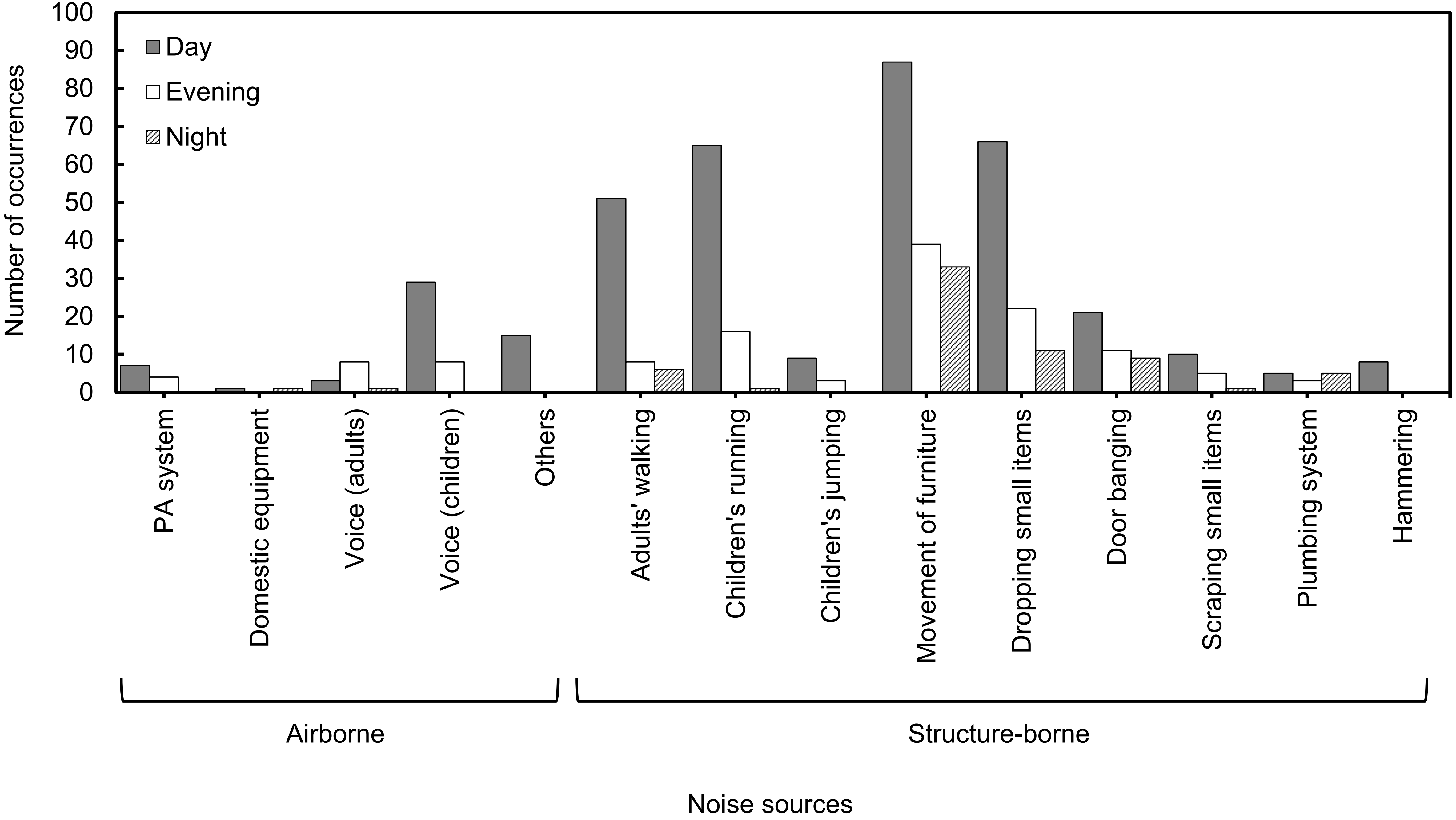
Figure 3. Boxplots of A-weighted sound exposure levels (L_{AE}) for noise sources; airborne sound sources (grey boxes) and structure-borne sound sources (white boxes).

Figure 4. Boxplots of A-weighted maximum sound pressure levels (L_{AFmax}) for noise source; airborne sound sources (grey boxes) and structure-borne sound sources (white boxes).

Figure 5. Relationships between noise levels and slab thickness.

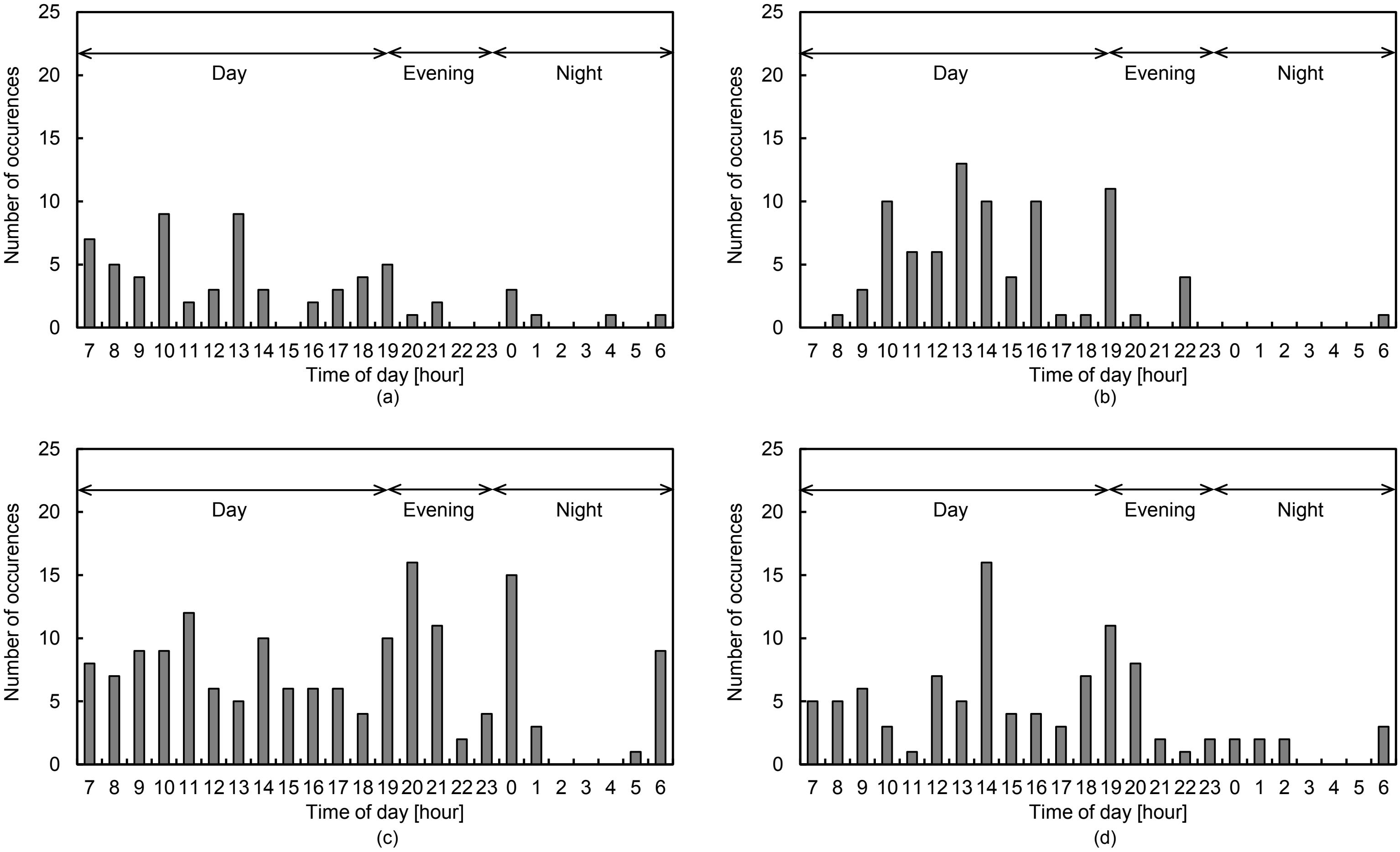
Figure 6. Relationships between the number of occurrences of noise sources and $L_{Aeq,24\text{-}h}$ for Groups 1 and 2.

Figure 1



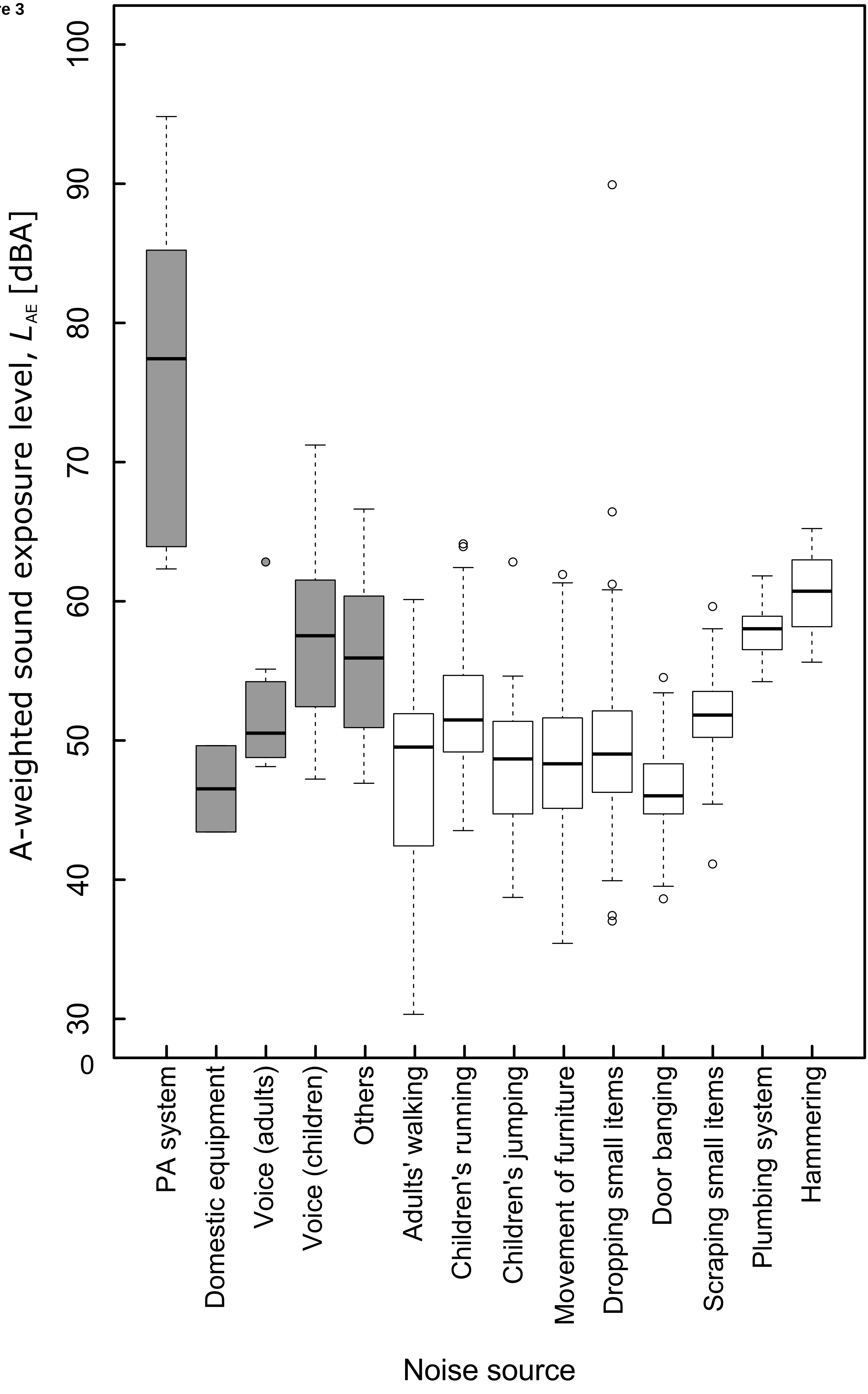
100
90
80
70
60
50
40
30
20
10
0
Number of occurrences
Day
Evening
Night
PA system
Domestic equipment
Voice (adults)
Voice (children)
Others
Adults' walking
Children's running
Children's jumping
Movement of furniture
Dropping small items
Door banging
Scraping small items
Plumbing system
Hammering
Airborne
Structure-borne
Noise sources

Figure 2



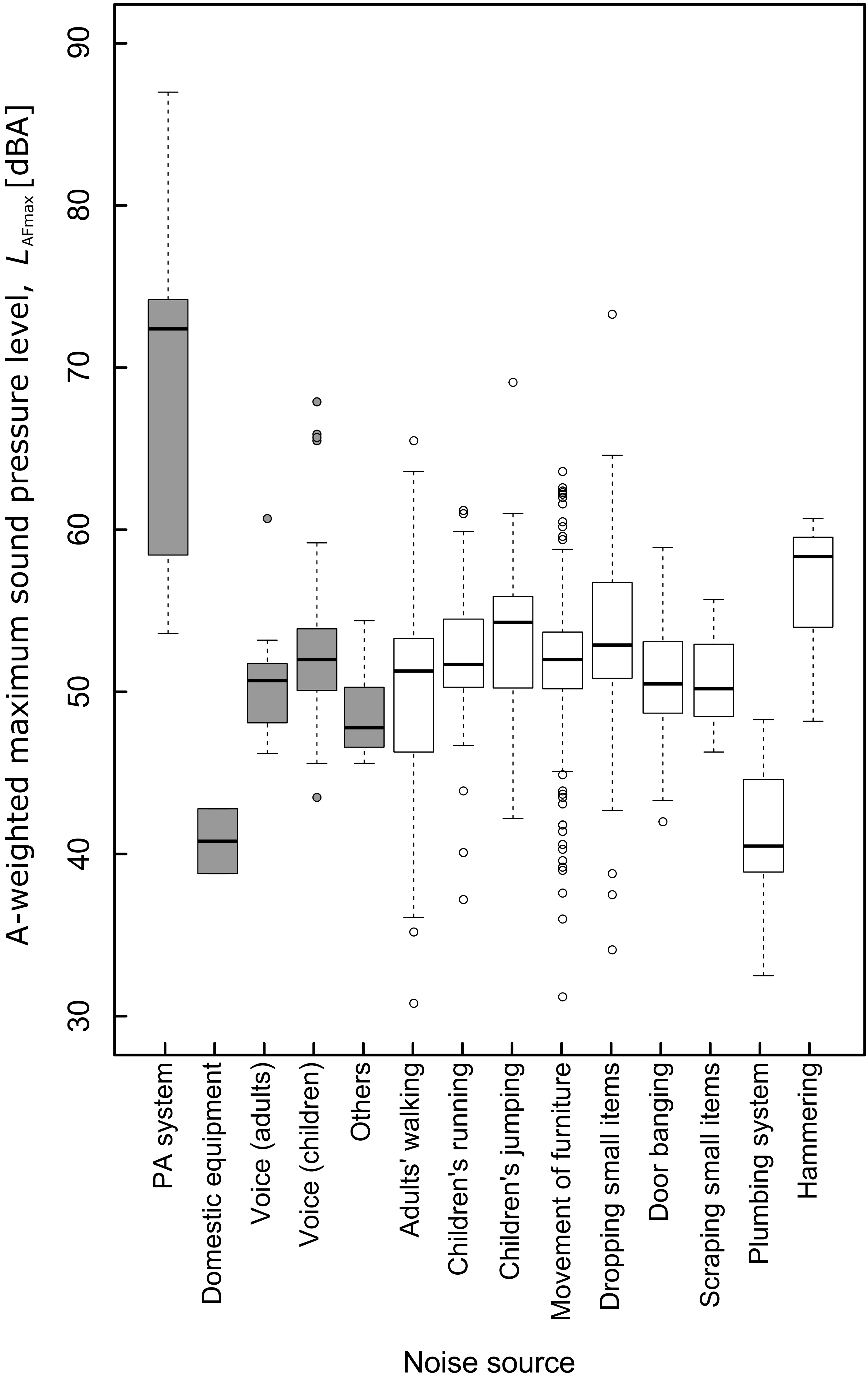
(a)
(b)
(c)
(d)
Day
Evening
Night
Number of occurences
Time of day [hour]

Figure 3



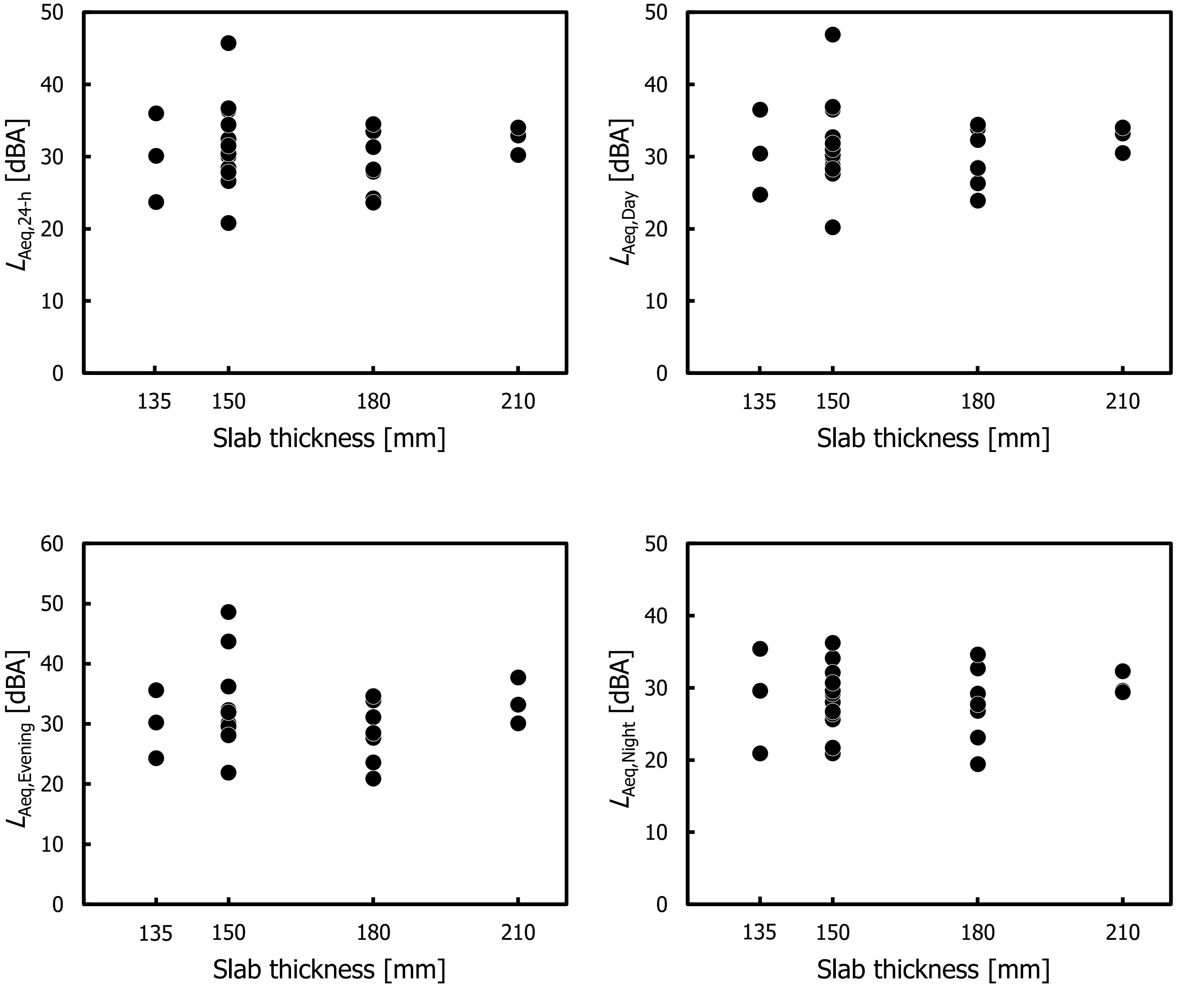
A-weighted sound exposure level, L_{AE} [dBA]
100
90
80
70
60
50
40
30
0
PA system
Domestic equipment
Voice (adults)
Voice (children)
Others
Adults' walking
Children's running
Children's jumping
Movement of furniture
Dropping small items
Door banging
Scraping small items
Plumbing system
Hammering
Noise source

Figure 4



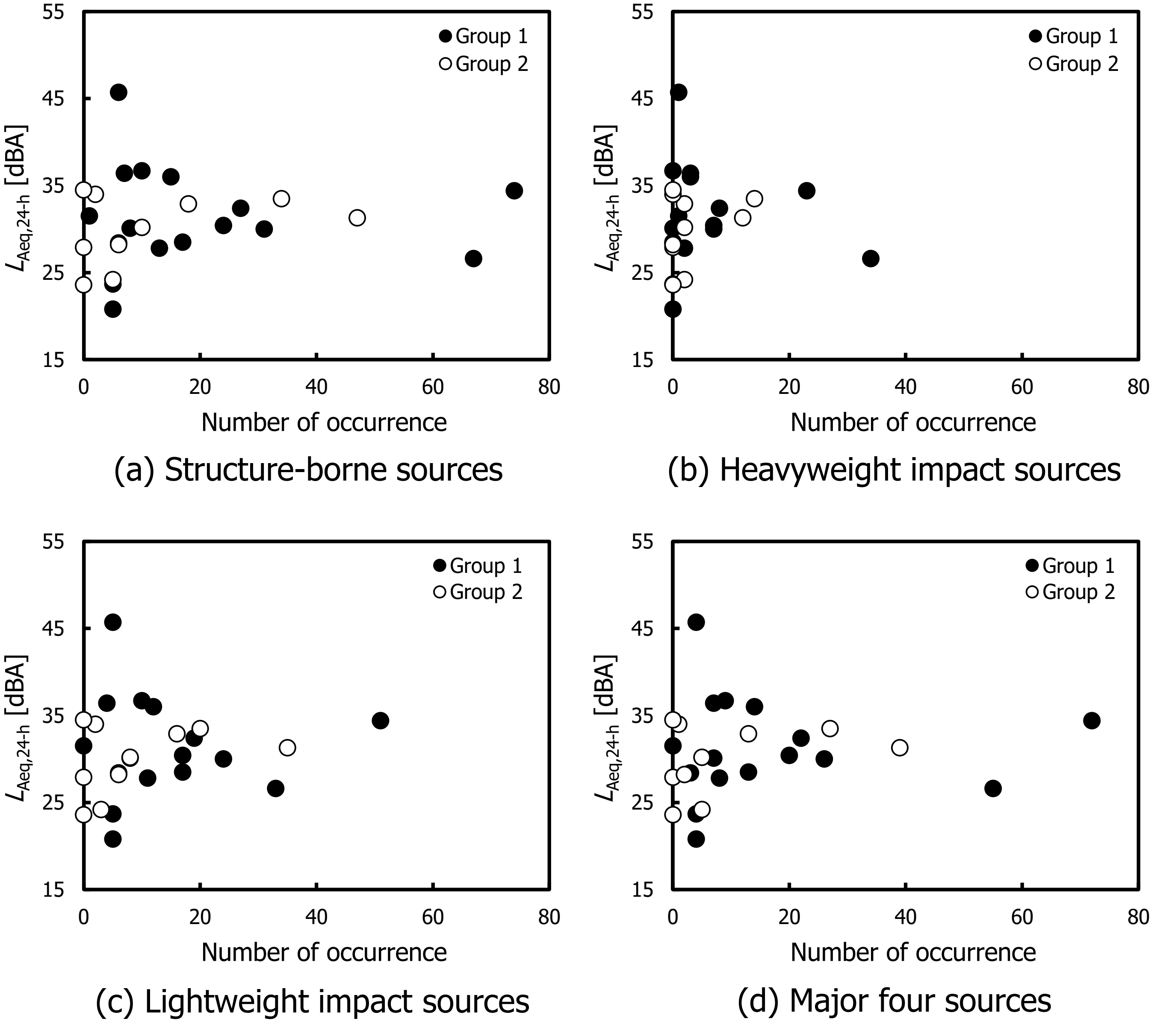
A-weighted maximum sound pressure level, L_{AFmax} [dBA]
30
40
50
60
70
80
90
PA system
Domestic equipment
Voice (adults)
Voice (children)
Others
Adults' walking
Children's running
Children's jumping
Movement of furniture
Dropping small items
Door banging
Scraping small items
Plumbing system
Hammering
Noise source

Figure 5



50
40
30
20
10
0
$L_{Aeq,24\text{-}h}$ [dBA]
135
150
180
210
Slab thickness [mm]
50
40
30
20
10
0
$L_{Aeq,Day}$ [dBA]
135
150
180
210
Slab thickness [mm]
60
50
40
30
20
10
0
$L_{Aeq,Evening}$ [dBA]
135
150
180
210
Slab thickness [mm]
50
40
30
20
10
0
$L_{Aeq,Night}$ [dBA]
135
150
180
210
Slab thickness [mm]

Figure 6



55
45
35
25
15
0
20
40
60
80
$L_{Aeq,24\text{-}h}$ [dBA]
Number of occurrence
Group 1
Group 2
(a) Structure-borne sources
(b) Heavyweight impact sources
(c) Lightweight impact sources
(d) Major four sources