# Effects of floor impact noise on people – annoyance and physiological responses

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### ABSTRACT

This paper summarises a series of studies focusing on neighbour noise, particularly floor impact noise mostly induced by footsteps. First, an in-depth interview was conducted to understand perception of floor impact noise and a conceptual model indicating the relationships between the key themes was developed. Second, a questionnaire survey was conducted to validate the aforementioned conceptual model. Significant relationships of annoyance and non-acoustic factors were found. Third, 24-hour noise measurements were performed in residential buildings to investigate sources, levels, lengths, and number of occurrences of neighbour noise. Major heavyweight impact sources and range of their noise levels were then identified. Fourth, two laboratory experiments were carried out to investigate annoyance and physiological responses to floor impact noise. Effects of acoustic and non-acoustic factors on the responses were examined. Finally, a sentiment study was conducted to further examine the perception of floor impact noise. Effects of acoustic and non-acoustic factors on sentiment ratings and annoyance were explored.

## INTRODUCTION

It has been known that environmental noise annoyance is affected by not only acoustic factors but also non-acoustic factors [1-4]. In particular, aircraft noise annoyance was found to be affected by frequency of over-flight and noise level [1], and annoyance caused by railway, aircraft, and road traffic noises was reported to be influenced by noise level [2]. Noise source is another significant factor that has been found to influence environmental noise annoyance [3-5]. In addition, noise sensitivity has been reported to affect environmental noise annoyance including road traffic or aircraft noise annoyance [6-8]. Moreover, attitude towards either noise or noise source has been known as a significant factor affecting annoyance [9-11]. Despite a number of studies have reported the impact of environment noise on health, few studies have dealt with building noise [12-14]. Noise source was found to affect dwelling noise annoyance [12; 13] and noise sensitivity significantly altered annoyance caused by noises in residential buildings [14].

A series of studies were conducted to understand how residents in multi-family residential buildings react to neighbour noise using different research methods. Firstly, a qualitative study was conducted to understand people's responses when they are exposed to neighbour noise in their homes. The findings from the qualitative study were then validated by the second study using a quantitative method. Next, noise sources, noise levels, lengths, and number of occurrences of major noise events in real residences were identified through field measurements. In addition, two laboratory experiments were designed based on the previous findings and conducted to investigate physiological responses, annoyance, and sentiment changes induced by floor impact noise. Real impact sources as well as standard impact source were used in the laboratory experiments.

## PERCEPTION OF AND REACTIONS TO FLOOR IMPACT NOISE

A qualitative study was carried out in order to gain knowledge of how people react when they are exposed to neighbour noise in multi-family residential buildings [15]. From in-depth interviews with a sample of adults, key themes and categories were identified using a methodology of grounded theory [16]. The identified themes and categories were then used for developing a conceptual model explaining responses to floor impact noise.

### Conceptual model

In-depth interviews were conducted with residents (*N*=14) who lived in multi-family residential buildings. The methodology of grounded theory was adopted as it allows substantial data and insight in research data to be yielded, and is useful to comprehend underlying mechanisms of certain phenomena. The interview questions were open-ended and depended on responses of the interviewees. Each interview was manually coded line by line using the interviewee's own words and immediate expressions. The codes were classified into several themes, and those with significant relationships and similarities were grouped together in higher-order categories. No new insight was obtained after the interview of the 13th participant, and theoretical saturation [16] was thus considered to have been attained after one additional interview. The numerous processes of the manual and computerised coding enabled a comprehensive analysis of the data and an identification of the core themes and categories.

The identified themes were grouped into four key categories (noise exposure, noise perception, noise reaction, and intervening conditions). Of the four categories, the term 'intervening conditions' included underlying psychological factors that were observed to interact with the other categories [16]. A conceptual model (Figure 1) was then developed mainly based on previously suggested models of environmental noise [17-19]. This model illustrates relationships among the identified themes under the four categories. Three categories are illustrated to be tied in a loop, and 'intervening conditions' is reciprocally related to this whole loop. It implies 'intervening conditions' have inter-relationships with all the other themes in other categories. Similar to previous studies [26-28], the themes under 'intervening conditions' were found to be closely and reciprocally linked to the themes under the other categories. It was also found that attitudinal factors and noise sensitivity have close relationships with the themes under the other categories such as annoyance and coping, confirming the previous findings from environmental noise [18-21]. Another extended finding of this study is the effects of 'intervening conditions' on noise exposure. Some participants reported that their neighbours produced retaliatory (revengeful) noise after they complained about the noise. Thus, it was hypothesised that a problematic relationship with upstairs neighbours (which is regarded as one of the attitudes to neighbours) may increase the occurrence of retaliatory noise from upstairs.

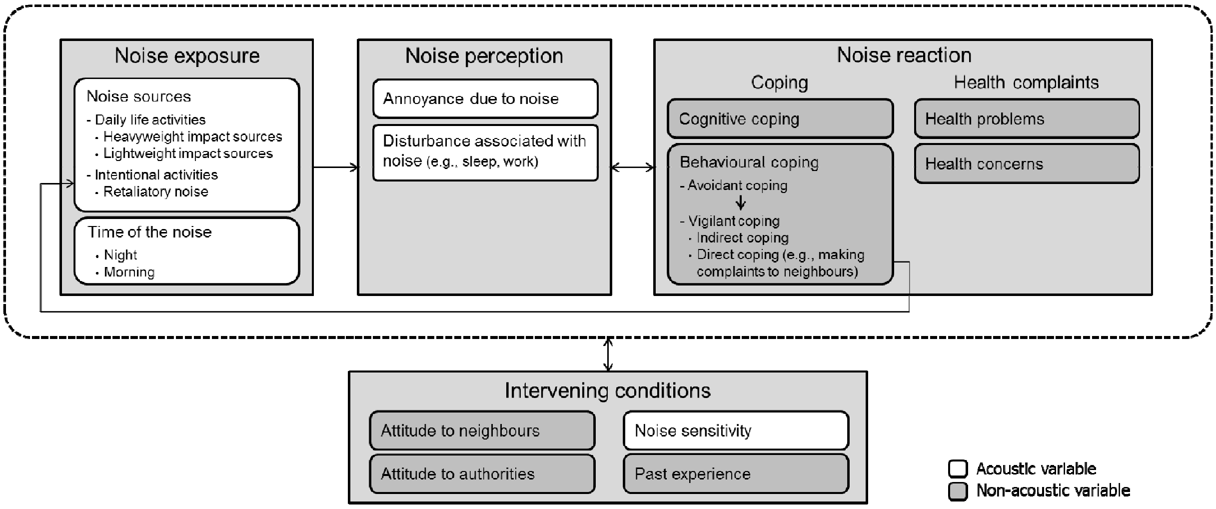


**Figure 1:** Conceptual model of perception and reaction to floor impact noise [15]

## RELATIONSHIP BETWEEN FLOOR IMPACT NOISE ANNOYANCE AND NON-ACOUSTIC FACTORS

A quantitative study was carried out in order to test the previously developed conceptual model [22]. The hypothesised causal model was validated using structural equation modelling (SEM) with survey data from residents living in multi-family residential buildings.

### Testing the conceptual model

A causal model was hypothesised based on the previously developed conceptual model. A social survey was then designed to contain question items about noise sensitivity, disturbance, annoyance, health complaints, coping, and attitudinal factors. The responses from the survey ($N$=487) were analysed using structural equation modelling. This statistical procedure was chosen since it estimates multiple and interrelated relationships simultaneously, calculates measurement error in the estimation process, and describes a model which explains the entire set of relationships [23].

As shown in Figure 2, four of six hypothesised paths were statistically significant. It was found that noise sensitivity increased disturbance; disturbance increased annoyance. Annoyance also significantly affected both coping and health complaints as previous theoretical and empirical studies on environmental noise have suggested [17-21]. However, contrary to previous empirical studies [20; 21], two attitudinal factors had no significant impacts on coping. This might be explained by three reasons. First, different measurement of coping was used. Contrary to the previous studies which asked their participants about cognitive coping [20; 21], this survey focused on asking behavioural coping which was dominantly found in the previous interview study. Second, the noise sources were different. This study measured attitudes to noise source with which the participants can have personal relationships, whereas the noise sources of the other studies [20; 21] were aircraft and railway with which people cannot have personal relationships. The previous studies [20; 21] measured attitudes to noise sources by asking their participants about the importance or financial benefits of the noise sources; but this study asked the participants how close they were with their upstairs neighbours. Third, the relationships between authorities and the noise sources were different. The attitudes towards authorities assessed in this study were not of the kind that the others [20; 21]. The occurrence of aircraft and railway noise can be ascribed to relevant authorities such as airports, railway institutes, or the governments since the noise sources are regarded as being run by the authorities; in contrast, the sources of floor impact noises are simply the upstairs neighbours.

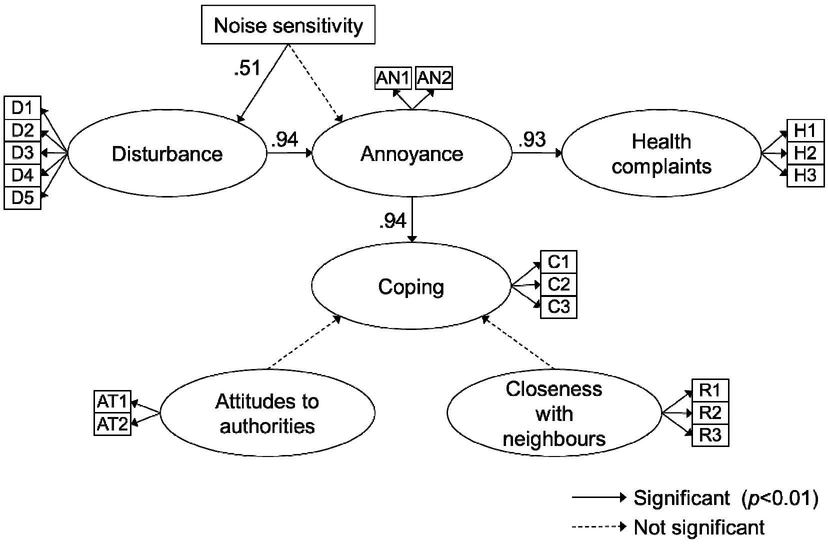


**Figure 2:** Tested structural equation model [22]

## NEIGHBOUR NOISE IN REAL RESIDENCES

Noise measurements for 24 hours were carried out in real residences ($N$=26) to examine different sources of neighbour noise and their levels, lengths, and how many times they occurred [24].

### Noise sources, number of occurrences, lengths, and levels

All noise measurements were carried out under unoccupied conditions. All windows were double glazed and closed during the measurements to minimise the effects of outdoor noise. All measurements were also conducted only during weekdays to avoid influences of neighbour's daily activities on the recordings. Only noise events exceeding the threshold levels for day and night based on the WHO recommendation for dwelling noises were analysed: 35 dBA ($L_{Aeq}$) for day; 30 dBA ($L_{Aeq}$) and 45 dBA ($L_{AFmax}$) for night. The threshold $L_{AFmax}$ for the daytime as 50 dBA was also adopted, in accordance with the domestic guidelines of the Korean Government.

As shown in Figure 3, all noise sources were grouped into airborne and structure-borne noises. Of structure-borne noise sources, heavyweight and lightweight impact sources were identified. It was found that structure-borne noise sources occurred dominantly. The number of occurrences of movement of furniture (e.g., chairs, tables etc.) was the largest, followed by dropping of small items, children's running, and adults' walking; they accounted for approximately 80% of all the noise events. Low number of occurrences does not guarantee acoustic comfort in dwellings because this study only counted noise events exceeding threshold noise levels. In addition, lengths of the noise events were very diverse. Door banging was very short (median=3.3s), whereas noise from the plumbing system lasted longer (median=108s). Other sources such as musical instruments showed the largest duration (maximum=428.5s). Since each noise event lasted for different time length, 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. As presented in Figure 4, PA system showed the highest median noise level, followed by voice of children among the airborne noise sources. Among the structure-borne sources, hammering and door banging produced the highest and lowest median noise levels, respectively.

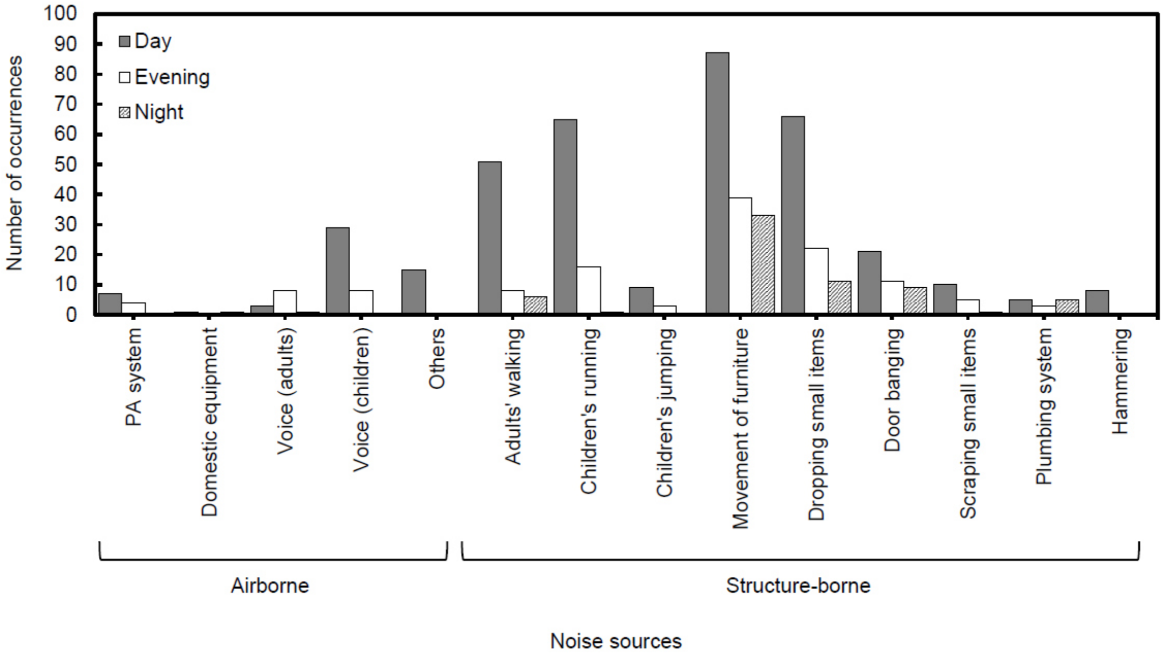


**Figure 3:** Number of occurrences of different noise sources [24]

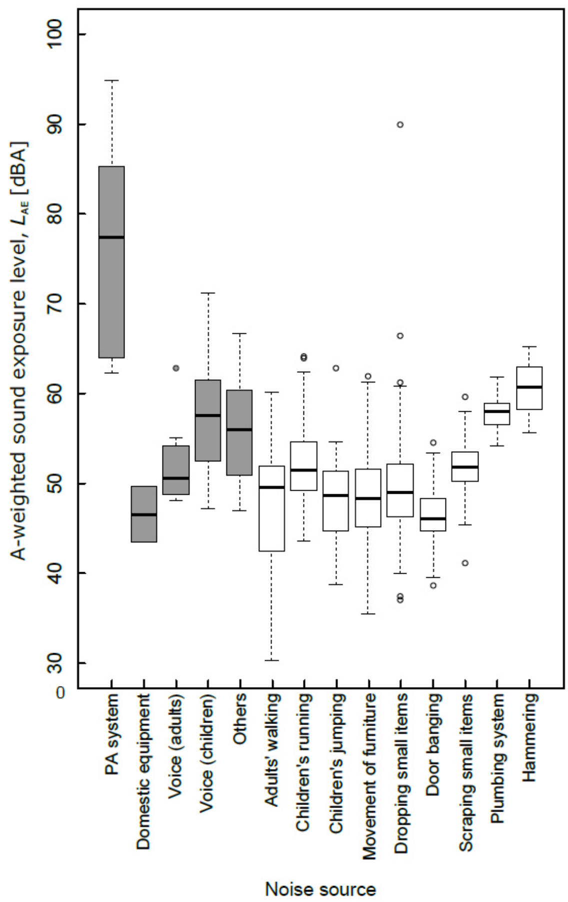


**Figure 4:** A-weighted sound exposure levels ($L_{AE}$) of different noise sources: airborne sound sources (grey boxes) and structure-borne sound sources (white boxes) [24]

## ANNOYANCE AND PHYSIOLOGICAL RESPONSES TO FLOOR IMPACT NOISE

Two laboratory experiments were conducted to examine annoyance and physiological responses to floor impact noise [25]. Both experiments introduced two different floor impact noises induced by a standard heavyweight impact source (i.e., an impact ball [26]) and real impact sources such as human footsteps. The participants (*N*=21) in the first experiment rated annoyance to 8-second noise stimuli and their physiological responses were measured when 23-second noise stimuli were presented. The second experiment recruited 34 participants and presented 5-minute noise stimuli for measuring all the responses. In both experiments, three simple physiological measures were used: 1) heart rate (HR) expressed in beats per minute (BPM), 2) electrodermal activity (EDA) expressed in microsiemens (µS), and 3) respiratory rate (RR) expressed in beats per minute (BPM). Effects of noise levels, noise sources, noise sensitivity, and duration of noise exposure on psycho-physiological responses were investigated throughout the experiments.

### Annoyance

Figure 5 shows the mean magnitude estimation of annoyance for 8-second noise stimuli. It was found that annoyance was affected by noise levels and noise sources. Annoyance increased as the noise level increased for both standard and real impact sources. Annoyance ratings of the standard impact source (i.e., an impact ball) were found to be consistently higher than those of the real impact sources (i.e., lightweight and heavyweight impact sources, such as dropping of a toy and human footsteps). It was notable that the standard deviation (error bars) also increased along with the increasing noise level for both sources. In addition, the differences between the two sources were significant at all levels.

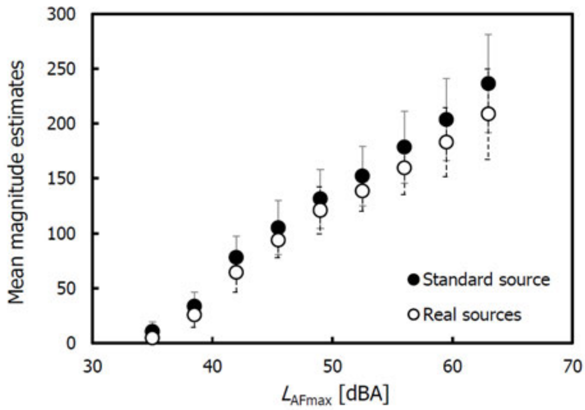


**Figure 5:** Magnitude estimation of annoyance rated to 23-second noise stimuli [25]

Figure 6 shows the annoyance ratings for 5-minute noise stimuli which were measured by an 11-point scale. Similarly, annoyance was affected by noise levels, noise sources, and noise sensitivity. Annoyance increased as the noise level increased for both the standard and the real impact sources. Annoyance ratings of the reference noise (road traffic noise, RTN) also increased along with the increase of the noise level. However, annoyance ratings of the standard impact source were consistently lower than those of the real impact sources. Statistical significances between the annoyance ratings of the standard and the real impact sources were found at 40 and 60 dBA. This is not consistent with the previous finding in Figure 5 indicating the opposite tendencies. This could be explained by different length of noise stimuli (8-second vs. 5-minute) and different presentation of the standard impact noise. In the first experiment, the standard impact noise stimuli were presented at regular intervals, whereas the impact ball noises were edited to simulate the human footstep noise in the second experiment.

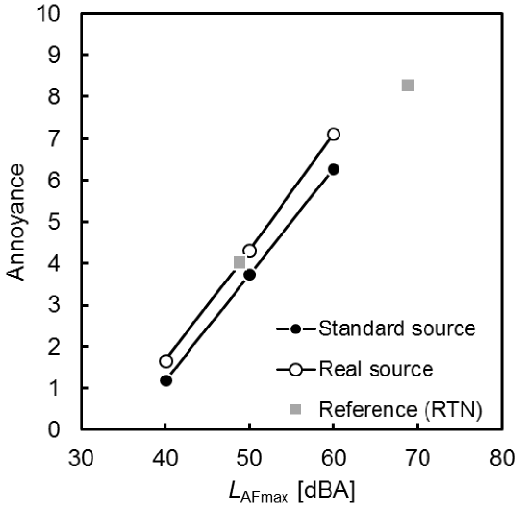


**Figure 6:** Annoyance rated to 5-minute noise stimuli

## Physiological responses

Physiological responses were significantly changed when the 23-second noise stimuli were presented in the first experiment. As shown in Figure 7, heart rate (HR) decelerated, electrodermal activity (EDA) increased, and respiratory rate (RR) accelerated. These changes imply that arousal status was experienced when the noise stimuli were presented [27]. Noise sources (standard vs. real) had no effect on the physiological responses, whereas different noise levels significantly affected changes in EDA and RR.

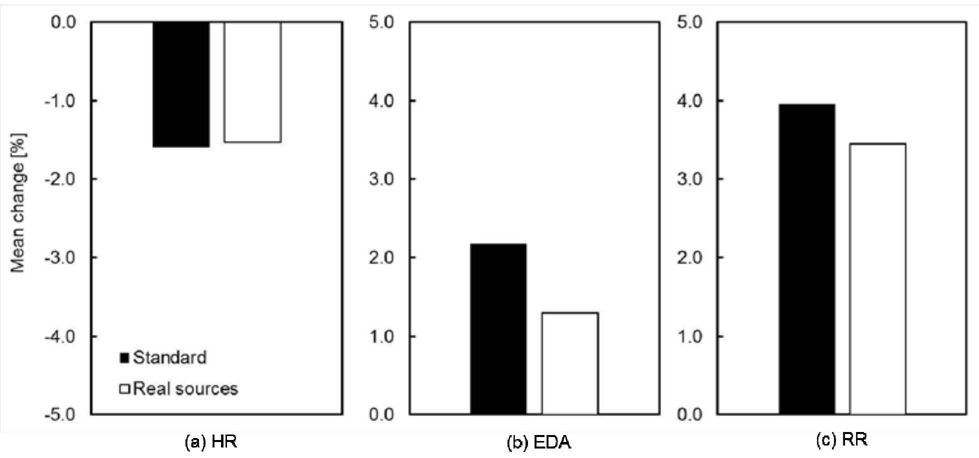


**Figure 7:** Changes of the physiological responses when the 23-second stimuli were presented [25]

Contrary to the first experiment, both noise levels and noise sources had no impact on the physiological responses when the 5-minute noise stimuli were presented in the second experiment. However, noise sensitivity and duration of noise exposure significantly affected the physiological responses. As presented in Figure 8, HR decelerated, EDA increased, and RR accelerated when the participants were initially exposed to the stimuli, indicating arousal status being experienced [27]; these changes were in agreement with the findings from the first experiment. Additionally, it was found that HR accelerated, EDA decreased, and RR decelerated as the duration of noise exposure increased. In other words, the longer the participants were exposed to the noise, the more their physiological responses habituated [28]. Moreover, differences between the low and high noise-sensitivity groups' physiological responses were significant. The low noise-sensitivity group showed smaller changes (smaller deceleration in HR, and smaller increases in EDA and RR) than the responses of the high noise-sensitive group.

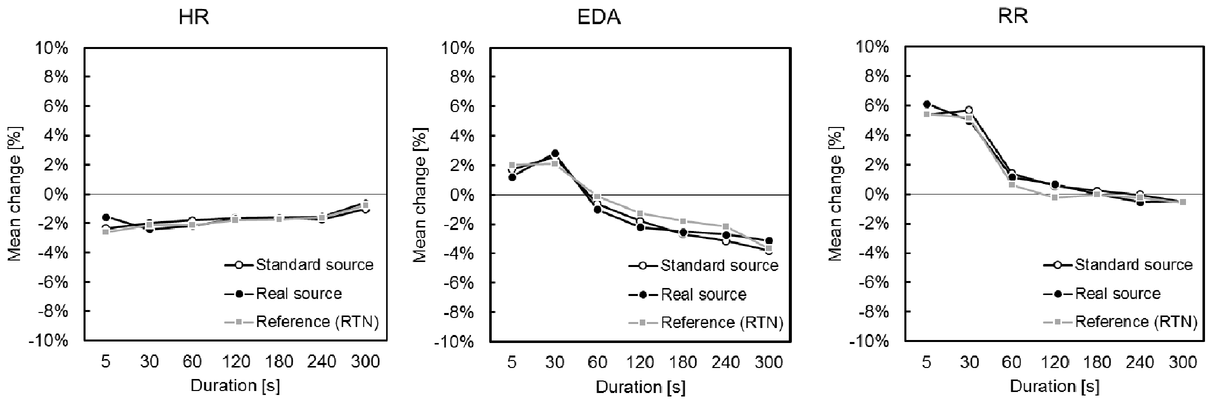


**Figure 8:** Changes of the physiological responses when the 5-minute stimuli were presented

## SENTIMENT ANALYSIS

A sentiment analysis was conducted in order to further examine people's emotion to floor impact noise. Participants were asked to rate anger, sadness, and annoyance when standard impact noise and real impact noise were presented at different noise levels.

### Sentiment and annoyance changes

A number of sentiment lexicons were first collected from various data such as the transcripts of the in-depth interview [15], published reports, and online postings about floor impact noise complaints. A preliminary survey was performed with 223 residents living in multi-family residential buildings. A hierarchical clustering method was employed to classify the lexicons into two groups (i.e., anger and sadness). Top 20 lexicons were then chosen to be used as the final lexicons for the main study. The standard impact noise and the real impact noise were presented to participants (*N*=41) at different noise levels in the laboratory. The participants were asked to respond to a questionnaire presenting a list of lexicons related to anger and sadness when the noise stimuli were randomly presented. This study aimed to investigate the influences of noise levels, noise sources, and noise sensitivity on sentiment changes and annoyance.

It was found that the anger and sadness were significantly affected by noise levels and noise sources. As presented in Figure 9, ratings of anger-lexicons and sadness-lexicons increased as the noise level increased. The responses to the real impact noise were constantly higher than those to the standard impact sources above 40 dBA and the differences of the anger between the two sources were significant above 40 dBA. The differences of the sadness between the two sources were also significant above 50 dBA. Annoyance was significantly affected by noise levels but not by noise sources. Similarly, annoyance increased with the increasing noise level for both sources and differences between the two sources were not observed. Noise sensitivity was correlated with annoyance ratings of the real impact noise and anger of the real impact noise. Other non-acoustic factors such as gender, age, length of residency did not have any relationship with the responses. In addition, annoyance had significant correlations with anger and sadness.

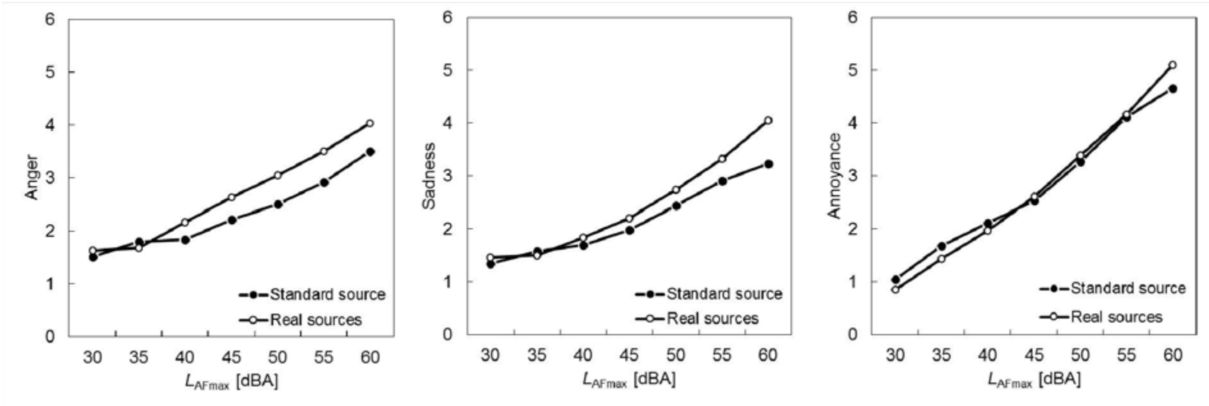


**Figure 9:** Changes of anger, sadness, and annoyance as the noise level increased

Figure 10 illustrates the subjective ratings of low and high noise-sensitivity groups. All the ratings of the low noise-sensitivity group were consistently lower than those of the high-sensitivity group. The differences between the two groups were significant across the ratings.

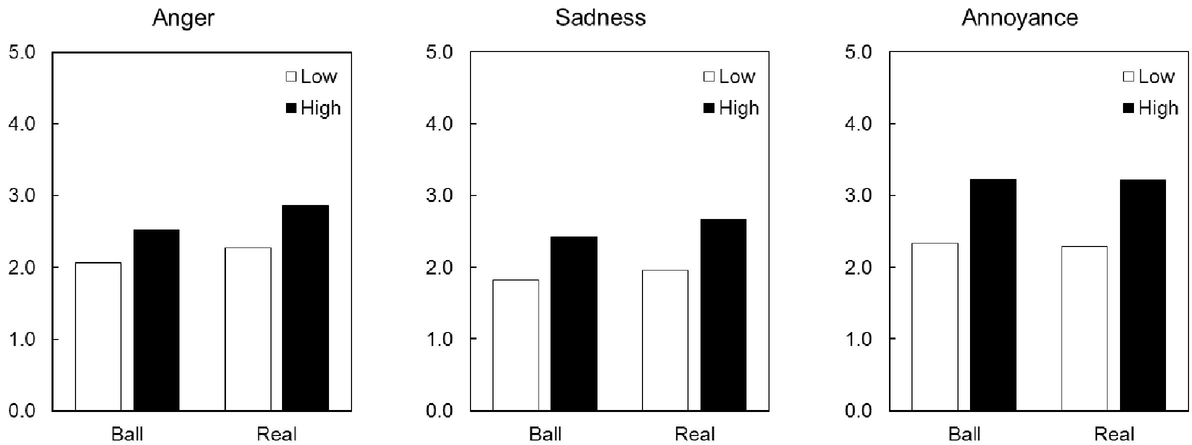


**Figure 10:** Differences between low and high noise-sensitive groups' mean ratings to anger, sadness, and annoyance

## CONCLUSION

A series of studies were carried out in order to provide a further understanding of how people perceive and react to neighbour noise heard in their residences. A conceptual model explaining relationships among various factors was developed from the in-depth interviews; this model was then validated by the questionnaire survey. It was found that noise sensitivity had a significant influence on disturbance; disturbance had a significant impact on annoyance, and annoyance had effects on coping and health complaints. Field noise measurements reported that children's running and adults' walking noises were the most dominant heavyweight impact sources, while movement of furniture and dropping of small items were the most dominant lightweight impact sources. Two psycho-physiological experiments showed that noise levels, sources, and noise sensitivity significantly affected annoyance. Noise sensitivity was also found to significantly influence the physiological responses to floor impact noise. Sentiment analysis shows that ratings of anger and sadness increased as the noise level increased, and the ratings were affected by noise sources. Noise sensitivity was significantly correlated with annoyance and both sentiment lexicons (i.e. anger and sadness).

The present study only focused on heavyweight buildings (reinforced concrete) because they are the majority types of residential buildings in South Korea. It would be helpful to investigate lightweight buildings for a wider understanding of psycho-physiological responses to floor impact noise. Particularly, given that residents in South Korea live indoors without shoes, a comparative study between different life-styles (e.g., those who wear shoes indoors) would yield further insight into understanding dwelling noise. In addition, long-term responses in situ could provide a deeper understanding of psycho-physiological responses.

**Acknowledgements**

This research was supported by a grant from a Strategic Research Project (A study on noise reduction solution for adjacency household in apartment house) funded by the Korea Institute of Civil Engineering and Building Technology.

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