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Perception of combined indoor noise sources in lightweight buildings

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ABSTRACT

Contrary to community noise field, the combined effect of multiple noise sources on annoyance have not been investigated in building acoustics. Therefore, the present study aims to quantify the total annoyance and emotional reaction caused by indoor noises from the upstairs and next-door neighbours. Footstep sounds were recorded in a laboratory equipped with a timber joists floor in different configurations. Listening tests were then performed to assess the relationship between psychological variables (annoyance, arousal, and valence), physiological measurements (fEMG, EDA, heart rate and respiration rate) and sound stimuli in several scenarios. In the first part, the perception of individual impact and airborne noise was evaluated considering the sound insulation performances of different wall and floor structures. The participants were also asked to evaluate the total annoyance, arousal and valence in the second part when impact and airborne sound sources were presented at the same time. Annoyance ratings for both single and combined noise sources were mainly affected by the sound pressure level; however, *sharpness* also contributed to the annoyance ratings. It was also observed that the annoyance ratings of the combined noise sources were influenced by the sound insulation performances of the wall and floor. The findings of this study would be helpful to understand how we perceive the combination of noise sources we are usually exposed in timber houses.

Keywords: Lightweight buildings, Annoyance, Combined noise sources

1. INTRODUCTION

Interest in lightweight constructions is flourishing in Europe. Timber buildings, in particular, offer a more environmentally sustainable alternative compared to traditional heavyweight constructions. However, acoustics comfort in such spaces is still not sustainable for dwellers. For instance, in multi-storey lightweight residential buildings, residents are frequently exposed to impact noise caused by upstairs neighbours as well as airborne noise transmitted from side units. This noise exposure negatively impacts the occupants causing stress and reducing the quality of psychological well-being in their home.

Annoyance due to combination of noise sources has been previously investigated in community noise field. As a result, different models have been proposed and tested in order to predict the total annoyance caused by environmental noise sources such as aircraft, road traffic and railway noise (1, 2). The combination of acoustic sources has also been studied to enhance urban soundscape. Particularly, adding water sounds to urban sound field resulted to be effective by masking urban noise such as construction sites and road traffic (3). Previous study also highlighted the key role of non-acoustic factors in the evaluation of the total annoyance caused by combination of noise sources (4). Moreover, noise sensitivity was an essential variable in understanding subjective responses to environmental and buildings noise, specially floor impact noise in apartment buildings (5). In order to assess noise sensitivity, NoiSeQ questionnaire was developed to identify noise resistant and noise sensitive individuals (6).

The perception of acoustic stimuli is influenced by its emotional experience. In particular, acoustic stimuli might evoke sensations and emotional reactions which may also imply or affect quality judgments (7). The perceived emotions can be recorded in the orthogonal dimensions of arousal and valence using Self-Assessment-Manikin Scale (SAM). A number of studies used this approach to evaluate reactions to acoustic stimuli (8, 9) shifting the focus toward listeners and contextual characteristics instead of physical characteristics of the signal.

The goal of the present study is to investigate the psycho-physiological responses to single and combined noise sources. It was hypothesized that psycho-physiological responses to noise might be different across types and combinations of noise sources. Floor impact noise transmitted from the upstairs neighbours was used as a major type of noise stimuli and airborne noise source from the side units was added to the floor impact noise. Laboratory experiments were conducted with 20 participants. Noise annoyance, arousal and valence were evaluated after each stimulus presentation, and four physiological measures (fEMG, EDA, heart rate and respiration rate) were monitored throughout the experiment.

2. METHODOLOGY

2.1 Participants

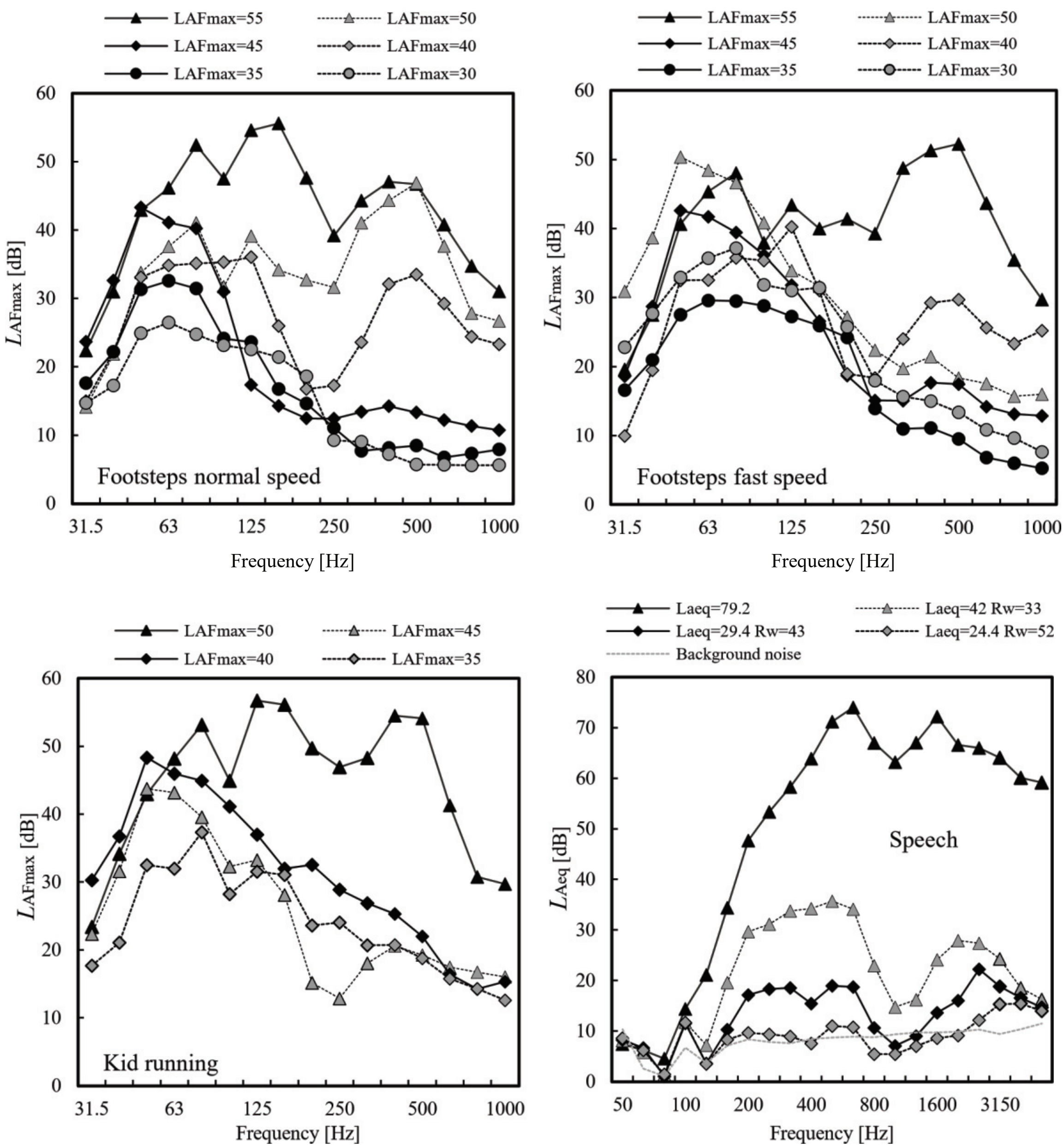
Twenty adults (8 males and 12 females) with self-reported normal hearing took part in the experiment so far. The participants aged between 22 and 33 (mean= 27.8 and std= 2.7) and their nationality varies across eight different countries. Seven of them reported to be commonly annoyed by neighbour noises in their actual house. The self-reported noise sensitivity measured using NoiSeQ ranged from 28 up to 70.

2.2 Noise stimuli

Five different noise sources were selected as representative of typical impact and airborne noises heard in residential buildings. Three of them are floor impact sources consisting of different footsteps: an adult walking at different paces (normal, 108 bpm and fast, 132 bpm) and a kid running. Others are airborne sources from neighbours: speech (conversation between two people) and piano music. Floor impact noises were recorded in the acoustics laboratory at Rosenheim University of Applied Science, where a lightweight timber joists floor is separating the vertically adjacent source and receiving rooms. The floor area of the receiving room was 21 m^2 and its volume was 53 m^3. Sound absorbing panels were installed in the receiving room so measured reverberation time of the receiving room was around 0.5 s. Sound recordings were carried out with four different configurations: 1) bare timber joists with chipboard on top; 2) bare timber joists and chipboard with sand floating floor installed; 3) bare timber joists and chipboard with suspended ceiling, and 4) bare timber joists with chipboard with suspended ceiling and floating floor. For each configuration, 5mm thick carpet on the floor was used as a floor finish and additional recording was also performed without floor covering. A female adult with a weight of 50 kg and a height of 1.65 m and a five years old child with a weight of 22 kg were chosen as general walkers. A-weighted maximum sound pressure levels (L_{AFmax}) were measured using a microphone (GRAS, 40HL) when adult and kid walked or ran diagonally in the source room. The L_{AFmax} of the adult walking ranged between 27 dB and 56 dB, while the kid running showed a smaller range from 33 dB to 51 dB. As listed in Table 1, the ranges of noise stimuli in the present study correspond to the range of the recordings. Thus, the adult walking varied between 30 and 55 dB as an interval of 5 dB, while, the level of the kid running changed from 35 to 50 dB. The sound recordings representing each level were chosen as noise stimuli. For example, 50 dB of the adult walking (normal pace) was recorded from the bare timber joists with chipboard on top and carpet. The airborne noise sources were anechoic recordings. The spectral characteristics of the airborne noise sources were modified to simulate three lightweight partitions with good, medium and poor sound insulation performances (R_w=52, 43, and 33 dB respectively). It was assumed that A-weighted equivalent sound pressure level (L_{Aeq}) of the speech and music 79 and 80 dB in the neighbour's houses (10); thus, the ranges of the filtered sound stimuli were slightly different. Frequency characteristics of the noise stimuli are plotted in Figure 1. Most noise stimuli had dominant sound energies at low frequencies below 100 Hz. However, several sounds also showed strong sound energies at high frequencies. Those were recorded on floor structures with a configuration not effective in reducing the transmission of noise in the high frequency range, such as with no floating floor or carpet.

Table 1 – Sound pressure levels of noise stimuli; L_{AFmax} for impact sources and L_{Aeq} for airborne sources

Source		Levels [dB]
Impact	Adult walking at normal speed	30 – 35 – 40 – 45 – 50 – 55
	Adult walking at fast speed	30 – 35 – 40 – 45 – 50 – 55
	Kid running	35 – 40 – 45 – 50
Airborne	Speech	24 – 29 – 42
	Music	25 – 29 – 44



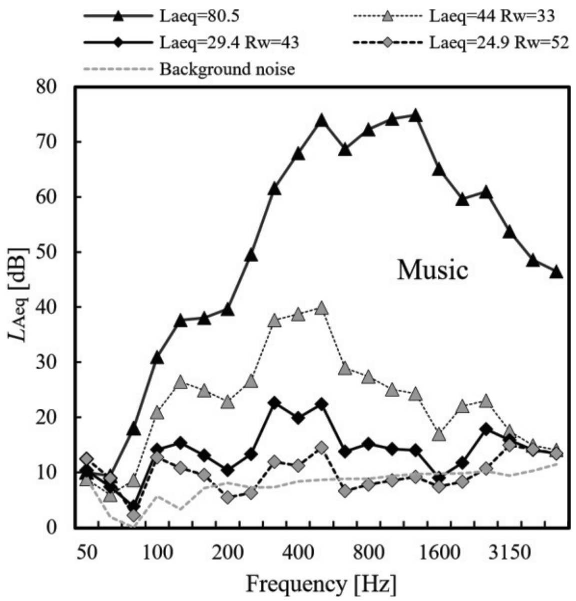


Figure 1 - Frequency characteristics of noise stimuli.

2.3 Experimental design

The experiment took place in an audiometric booth with low background noise level. Participants were sitting on a comfy chair and asked to answer questionnaire through VBA designed interface presented on a monitor. The stimuli were presented diotically through headphones (DT 770 Pro) and a subwoofer (SONAB System 9 CSW-71000) which was placed in front of the participants. Sounds above 63 Hz were presented via the headphones, while low-frequency sounds below 63 Hz were presented via the subwoofer. White noise (NC 25) was presented through headphones throughout the experiment as an ambient noise in the living room.

The experiment was composed of four sessions (three combined noise sessions and one single noise session). There were breaks between sessions to avoid excessive fatigue and loss of concentration. In the single noise session, each of the impact and airborne noise sources were presented for 15 minutes, while in the remaining sessions, the impact noise combined with airborne noise sources were presented for 21 minutes each. All noise sources and sessions were randomized across participants to avoid order effects. Each session consisted of the repetition of the following 40s sequence: 10s of baseline with a presentation of black screen; 20s of sound stimulus (single or combined noise sources) together with a picture of a living room on the screen; the final 10s for answering questions on the screen. Before the starting of the experiment participants were asked to answer the 35-items questionnaire NoiSeQ in order to assess their noise sensitivity. A training session was also designed as familiarizing phase with the noise stimuli and questionnaire form. During the experiments, participants were asked to imagine being relaxing in their own home. The study was ethically approved by the School of the Arts Committee on Research Ethics, University of Liverpool.

2.4 Assessments of psycho-physiological responses

After listening to each stimulus, the participants were asked to rate their annoyance on an 11-point scale (0 = '*Not at all*' and 10 = '*Extremely*'). Furthermore, two Self-Assessment Manikin (SAM) 9point pictorial scales were used to assess arousal and valence. In the present study, four physiological measures were investigated: 1) facial electromyography (fEMG), 2) electro dermal activity (EDA), 3) hart rate (HR) and 4) respiration rate (RR). All the physiological responses were recorded on a computer using a MP 150 WSW digital acquisition system (BIOPAC systems) and were analysed using AcqKnowledge 4.4 Software (BIOPAC systems).

3. RESULTS AND DISCUSSION

3.1 Psychological responses: annoyance

Figure 2 shows mean annoyance ratings for the single floor impact noises and the combinations of floor impact noise and speech noise (airborne). Specifically, thick black lines indicate the annoyance ratings of the single noises, while grey lines represent those of the combined noise sources. It was observed that the annoyance ratings increased as the increase of sound pressure level for three different impact sources (adults walking at normal and fast speed, a kid running). However, for the adults walking noises, the participants rated the stimuli at 45 dB less annoying than the stimuli at 40 dB. This is mainly because the stimuli at 40 dB had much stronger sound energies at high frequencies compared to other stimuli. It was also found that different sound insulation performances of the wall partitions significantly affected the annoyance ratings. For the highest sound insulation performance (R_w=52), the annoyance ratings of the combined noise sources were quite similar to those of the single noise sources without airborne noise source. On the other hand, other combined noise sources from the wall with R_w=43 and 33 showed significantly higher annoyance ratings than the single noise sources. More specifically, the influence of the addition of airborne noise sources to the floor impact noises was different across the sound pressure levels of the floor impact noises. The annoyance ratings of the floor impact noises ranged between 30 and 45 dB were remarkably increased with the addition of the airborne noise sources with R_w=43 and 33. The effect of the adding airborne noises on the annoyance ratings became less above 45 dB of the footsteps noise. For instance, for the impact sources at 55 dB, the annoyance ratings were already greater than 9 on an 11-point scale.

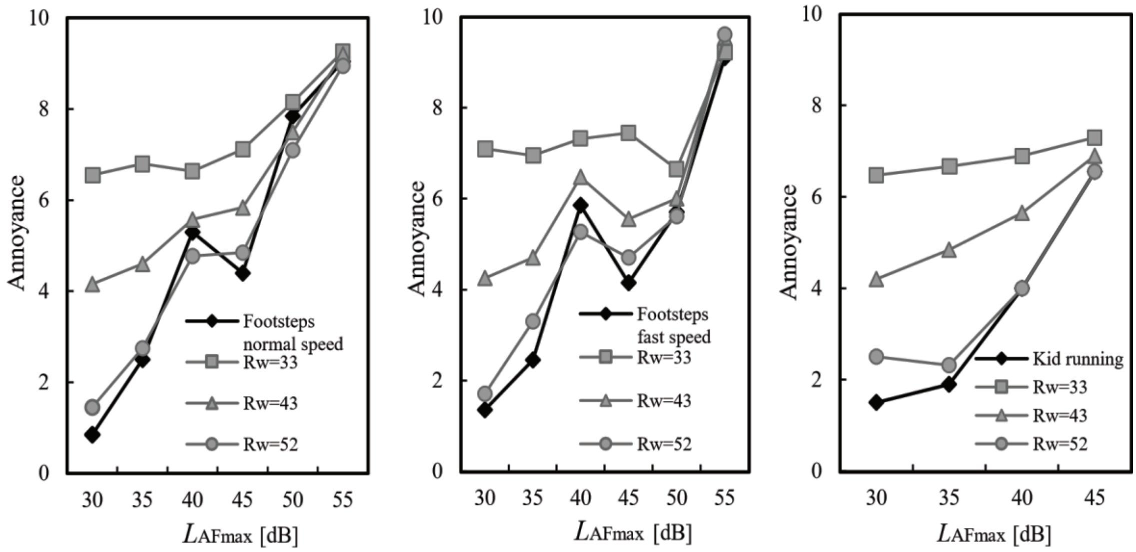


Figure 2 - Annoyance ratings for single and combined noise sources

3.2 Analysis of sound quality metrics

As shown in Figure 2, the annoyance ratings of the stimuli at 45 dB were lower than those of the stimuli at 40 dB for both normal and fast paces. This indicates that the sound pressure level is not sufficient to fully explain the annoyance ratings. Therefore, sound quality (SQ) metrics were introduced to understand the relationships between SQ metrics and annoyance ratings. *Loudness*, *sharpness*, *roughness* and *fluctuation strength* were calculated using BK Connect (Brüel & Kjær). *Loudness* was calculated according to ISO 532-1, which describes the procedures for calculating the time-varying *Loudness.* During the calculation of *roughness*, *sharpness*, and *fluctuation strength*, the time interval between the spectra was set at 2ms.

Multiple regression analysis was then conducted using a linear combination of SQ metrics to calculate the effects of SQ metrics on annoyance. It was found that the best combination of variables with respect to the correlation between the annoyance and SQ metrics was *loudness* and *sharpness*. The standardized partial regression coefficients of variables a_1 and a_2 in equation (1) were 0.64 and 0.38 respectively, and these coefficients were statistically significant ($p < 0.05$ for a_1 and a_2). Using these values, the obtained total coefficient (0.91) was significant (p<0.05). Coefficients a_1 and a_2 had positive values, therefore greater *loudness* and larger *sharpness* result in higher annoyance. As plotted in Figure 3, the annoyance ratings predicted by using equation 1 showed good agreements with the measured annoyance ratings.

$$Annoyance \approx a_1 loudness + a_2\, sharpness \qquad \text{(Eq 1)}$$

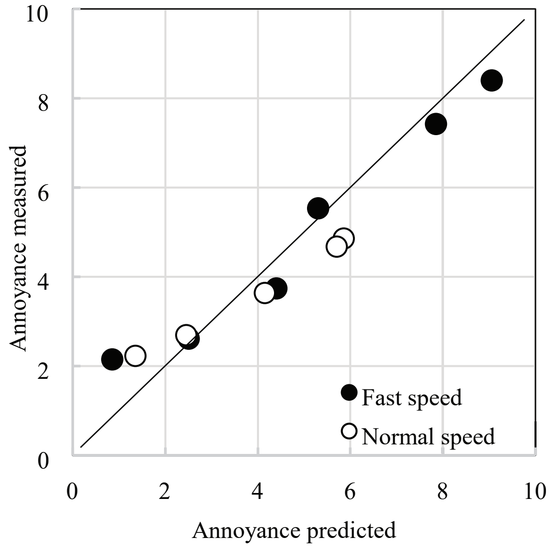


Figure 3 - Relationship between measured and predicted annoyance ratings for adults walking at normal and fast paces.

4. CONCLUSIONS

The present study measured the participants' subjective responses (annoyance, arousal and valence) and physiological responses (fEMG, EDA, heart rate and respiration rate) to single and combined noise sources commonly heard in lightweight residential dwellings. It was found that the annoyance ratings of the single noise sources were different from those of the floor impact noises combined with an airborne source (i.e. speech). The annoyance ratings of the combined noise sources were influenced by the sound insulation performances of the wall and floor. Analysis of the sound quality metrics also showed that the annoyance ratings were dependent not only on *loudness* but also *sharpness* related to the frequency characteristics of the noise stimuli. The laboratory experiment is still on-going and additional 20 participants will take part in this study. The results of the emotional dimensions (i.e. arousal and valence) will be presented together with the ongoing analysis of the physiological measurements at the conference.

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REFERENCES

1. Miedema HME. Relationship between exposure to multiple noise sources and noise annoyance. The Journal of the Acoustical Society of America. 2004;116(2):949-57.
2. Öhrström E, Barregård L, Andersson E, Skånberg A, Svensson H, Ängerheim P. Annoyance due to single and combined sound exposure from railway and road traffic. The Journal of the Acoustical Society of America. 2007;122(5):2642-52.
3. Jeon JY, Lee PJ, You J, Kang J. Perceptual assessment of quality of urban soundscapes with combined noise sources and water sounds. The Journal of the Acoustical Society of America. 2010;127(3):1357-66.
4. Pierrette M, Marquis-Favre C, Morel J, Rioux L, Vallet M, Viollon S, et al. Noise annoyance from industrial and road traffic combined noises: A survey and a total annoyance model comparison. Journal of Environmental Psychology. 2012;32(2):178-86.
5. Park SH, Lee PJ, Yang KS, Kim KW. Relationships between non-acoustic factors and subjective reactions to floor impact noise in apartment buildings. The Journal of the Acoustical Society of America. 2016;139(3):1158-67.
6. Schutte M, Marks A, Wenning E, Griefahn B. The development of the noise sensitivity questionnaire. Noise and Health. 2007;9(34):15-24.

7. Asutay E, Västfjäll D, Tajadura-Jiménez A, Genell A, Bergman P, Kleiner M. Emoacoustics: A study of the psychoacoustical and psychological dimensions of emotional sound design. Journal of the Audio Engineering Society. 2012;60(1/2):21-8.
8. Bradley MM, Lang PJ. Affective reactions to acoustic stimuli. Psychophysiology. 2000;37(2):204-15.
9. Tajadura-Jiménez A, Larsson P, Väljamäe A, Västfjäll D, Kleiner M. When room size matters: Acoustic influences on emotional responses to sounds. Emotion. 2010;10(3):416-22.
10. Hongisto V, Oliva D, Keränen J. Subjective and Objective Rating of Airborne Sound Insulation – Living Sounds. Acta Acustica united with Acustica. 2014;100(5):848-63.