Effects of spatial characteristics of footsteps sounds and non-acoustic factors on annoyance in lightweight timber buildings

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Running title: Effects of spatial characteristics on annoyance of footsteps sounds

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Abstract

This study investigates the effect of spatial characteristics of footsteps sounds from upstairs in wooden residential buildings together with the influence of non-acoustic factors on annoyance ratings. Footsteps sounds were recorded in the laboratory, where a typical lightweight timber joists floor is located between the source and receiving room. Two adults walked on the floor over three different paths (figure-of-eight, straight, and walking on the spot) at two different paces (very slow and normal). The spatial features of the recordings were quantified in terms of the magnitude of interaural cross-correlation (IACC) function. A total of 46 participants were recruited and they assessed their subjective annoyance after exposure to noise under laboratory conditions. During the laboratory experiments, 360-degree pictures of the living room during daytime or night-time were presented via a Head-Mounted Display (HMD). In addition, the participants were asked to answer the questions concerning noise sensitivity, chronotype, and attitude towards neighbours. Results showed that IACC had a significant effect on annoyance, showing an increase in annoyance with increasing IACC. Footsteps at a very slow pace were more annoying than those at a normal pace. It was also found that annoyance ratings with a presentation of the daytime living room were greater than those with a presence of the night-time living room. Furthermore, noise sensitivity, circadian rhythm, and attitude towards neighbours were significant in moderating annoyance ratings.

Keywords: footsteps sound, IACC, annoyance, noise sensitivity, chronotype, and attitude

1. Introduction

The spatial human auditory system is well developed in terms of source localisation for survival in everyday life. In particular, the spatial qualities of the sound may affect the way we perceive everyday sounds, including sounds from neighbours, such as footsteps. For example, a spacious sound field gives the impression of the source being wider and bigger, generating sounds that are perceived as more threatening [1]. Accordingly, it is necessary to measure both spatial and temporal factors of various environmental noises to effectively represent a subjective evaluation of sound sources [2]. The left hemisphere of the brain is specialised in the processing of temporal factors of sound signals, while spatial factors of sound signals are processed by the right hemisphere [2-5]. Hence, it was suggested that sounds with changes in both temporal and spatial factors might cause high annoyance due to the simultaneous stimulation of both hemispheres [6]. Sato, et al. [7] also argued that indices about sound pressure levels (SPL) and frequency characteristics of sounds cannot fully explain the psychological effects of noise on humans. They highlighted how the annoyance of moving sound sources is influenced by spatial factors that are extracted from the interaural cross-correlation function (IACF).

Several studies have examined the spatial factors of environmental noises such as aircraft noise [8, 9] and railway noise [10]. However, few investigations have been carried out to explore the spatial factors of commonly heard neighbours' sounds. In addition, there has been little agreement concerning the role of source movements on the subjective evaluation of floor impact sounds [7, 11-14]. Jeon [12] found that the perceived loudness of sound from standard impact sources (bang and tapping machines) could be represented by factors from the IACF as well as the autocorrelation function (ACF). More specifically, he argued that the spatial impression of the sound field can be explained by the magnitude of interaural cross-correlation (IACC). Later, Jeon, et al. [11] investigated the effects of a spatial factor (IACC) together with

SPL (L_{AFmax}) on the subjective evaluation of heavyweight floor impact sounds generated by a standard impact source (i.e. impact ball). In their study, annoyance increased with increasing SPL and decreasing IACC. The contributions of SPL and IACC to the scale value of annoyance were 79.3% and 20.4% respectively. This finding confirmed that spatial factors such as IACC should be considered in the evaluation of annoyance. Recently, Jo and Jeon [14] compared different experimental settings to develop a new assessment methodology for footsteps sounds in apartment buildings. They tried to introduce more detailed spatial characteristics of the sound source. They found that directional information through the head related transfer function (HRTF) significantly increased the annoyance of floor impact noise. However, the studies mentioned above, dealt with floor impact sounds in heavyweight buildings. In contrast, very few studies have examined spatial factors in lightweight buildings, and there has been disagreement regarding the effects of sound localisation on the annoyance of footsteps noise. Brunskog, et al. [13] compared a moving point source and a non-moving surface source and concluded that the sound localisation did not play a major role in the annoyance assessment. But they used convolved high heel walking sounds in a listening test and the floor structure was assumed to be a single-layered lightweight structure with a hard surface. On the other hand, it was found that spatial features of sounds influenced the subjective ratings of walking noise in timber buildings [15]. Späh, et al. [15] compared monaural and binaural impact sounds produced by real and standard sources. They found that binaural recordings caused significantly higher annoyance than monaural recordings. However, most impact sources did not move during the recording and only male and female walkers walked on a single path. In addition, the spatial features of binaural recordings were not quantified using objective measures. Therefore, it is necessary to clarify the effects of spatial factors on the annoyance of floor impact sounds using sound stimuli that were recorded with humans walking over various paths on a typical lightweight floor structure.

Walking pace has been considered to be a physical factor affecting floor impact noise; however, it is still unclear whether it affects residents' annoyance. Simmons, et al. [16] observed that the speed of the walker had a substantial effect on the annoyance in the dwelling below caused by the impact sound, and a slight increase in walking speed made the barely audible sound very unpleasant. Similarly, Ljunggren, et al. [17] reported that the impact sounds were often barely audible for normal and gentle speed walking, but they quickly became very disturbing as the walking speed increased. The importance of walking rate was also highlighted in another study [18] that investigated footfall noise in wood-frame building construction. Blazier Jr and DuPree [18] reported that an increase from a rather slow pace (80 steps per min., 1.3 s^{-1}) to a rapid walking (160 steps per min., 2.6 s^{-1}) produced a change of approximately 25 dB in the amplitude of floor vibration response at the fundamental frequency [18]. On the other hand, a recent laboratory study claimed that there was no significant difference in annoyance ratings between an adult walking at normal (1.8 s^{-1}) and fast (2.2 s^{-1}) paces on lightweight timber floors [19]. But it is unclear whether the very slow and normal pace of walking might lead to differences in annoyance ratings.

Non-acoustic factors play an important role in the subjective evaluation of sound. According to Job [20], noise exposure could account for approximately 20% of the variation in reactions to noise. Instead, attitude towards the noise source and noise sensitivity explained more variation in reaction than noise exposure. Guski [21] classified non-acoustic factors affecting annoyance into personal (e.g., noise sensitivity, chronotype, fear of harm connected with the source, personal evaluation of the source, and coping capacity) and social variables (e.g., attitude towards a sound source, history of noise exposure, and expectations of residents). Non-acoustical variables may also refer to situational and contextual factors such as the time of day at which the sound sources are heard [22, 23]. Among them, noise sensitivity has been extensively investigated as a moderating factor affecting annoyance with building and environmental noise [24-29]. Circadian rhythms affect several human body functions, including the regulation of auditory ones [30-33], and it was recently suggested that more attention to the influence of our circadian clock should be paid in auditory research [34]. Attitude towards neighbours is also identified as a key variable in mediating annoyance caused by neighbour sounds [35, 36], but it was not introduced in a laboratory setting. Therefore, more research is required concerning the effects of non-acoustic variables such as noise sensitivity, chronotype, and attitude towards the neighbours of participants in assessing annoyance of neighbour noise, together with the time of the day at which sound exposure occurs.

Within the context of urbanised landscapes and rapidly growing populations, lightweight constructions emerge as an alternative to non-wood constructions using steel and reinforced concrete. Multi-storey timber construction has become globally popular due to the recent rapid development of building technologies and a range of advanced mass timber products such as cross-laminated timber (CLT) and glued laminated timber (glulam). In particular, the number of multi-storey timber buildings has been growing since 1995 [37] and a growing number of high-rise timber buildings is appearing in the last decade [38]. Furthermore, the speed of assembly and the high quality deriving from prefabricated production allow the erection of multi-storey buildings containing prefabricated volumes within a short time and with minimal construction waste [39-41]. Acoustics conditions in the new residential spaces, framed by lightweight timber partitions with limited sound insulation performance, may lead to acoustic discomfort and noise annoyance [42, 43]. Accordingly, some researchers have started to focus on the perceived indoor acoustic environment in lightweight structures [19], and in particular on the subjective evaluation of floor impact sounds [44, 45].

The present study set out to investigate the effects of upstairs walker movements on noise annoyance in wooden residential buildings with consideration of non-acoustic factors. A laboratory experiment was performed in an anechoic chamber presenting several moving and steady footsteps sounds from upstairs. It was first hypothesised that different walking trajectories might cause variations in the spatial factor (i.e., IACC) of downstairs sound and annoyance ratings. It was also hypothesised that very slow and normal walking paces might influence annoyance ratings. Therefore, footsteps sounds were recorded while two walkers moved along different paths at very slow and normal paces on the lightweight floor structure. Third, it was assumed that footsteps sound heard in simulated daytime or night-time conditions would elicit different annoyance ratings. Thus, 360-degree pictures of a living room during day and night-time were presented via a head-mounted display (HMD). Lastly, it was hypothesised that the participants' personal and social variables such as noise sensitivity, chronotype, and attitude towards neighbours might moderate annoyance ratings. The participants, thus, were classified into two groups across the non-acoustic variables (e.g., low and high noise-sensitivity groups).

2. Methods

2.1. Participants

Participants were recruited after receiving ethical approval from the Ethics Committee of the National Institute of Advanced Industrial Science and Technology (AIST) and the Central Ethics Committee of the University of Liverpool. A total of 46 Japanese (29 males and 17 females) with self-reported normal hearing and aged between 20 and 60 years old (mean 23.7 std 6.6) took part in the experiment. It was assumed that the ethnicity of the participants has little impact because the majority of them have previously experienced the exposure to footsteps sounds in wooden buildings which were similar to those in floor structures in other countries like Europe. Before the experiment, each participant was asked to answer several questions about their demographic information, noise sensitivity, attitude towards neighbours and circadian rhythm type. Noise sensitivity was evaluated using a translated version of the 12-items questionnaire NoiSeQ-R [46] with an additional generic item ‘I am sensitive to noise’. According to their overall noise sensitivity score, the participants were then divided into low and high noise sensitivity groups. Attitude towards neighbours was assessed using five questions based on quotes from the interviewees [47] to identify the degree to which participants have a favourable attitude towards neighbours. Circadian rhythm was also evaluated using six items extracted from the 19-item morningness-eveningness questionnaire (MEQ) [48]. The six items were selected based on previous studies [49, 50] which considered their impact on the variance in the overall score of the extended MEQ version. Based on their overall score ranging from 5 to 27, the participants were categorised into three classes: 1) the definite or moderate morning-types (M-type), 2) the intermediate or day type (D-type), and 3) the definite or moderate evening-types (E-type). The questionnaire used in this study is listed in Supplementary Table S1 with its translation into Japanese.

2.2. Sound stimuli

Footsteps sounds were recorded in the building acoustics laboratory at the Rosenheim Technical University of Applied Science in Germany. In the laboratory, the source and receiving room were located one over the other and separated by a lightweight timber joist floor sample (14 m^2) which is a typical floor construction in European countries to achieve a good value of impact sound insulation in residential buildings. The floor structure was composed of 22 mm thick chipboard panel supported by timber joists (220 mm height and 80 mm width) with a spacing of 625 mm on centres equipped with a honeycomb 30 mm floating floor system filled with gravel. In this study, the footsteps sound of two individual walkers wearing socks were recorded as they walked on the floor alone. As shown in Figure 1(a), there were several trajectories to generate footsteps sounds with varying IACC. The walking trajectories included: 1) walking in a figure-of-eight (starting from P1), 2) walking along a straight line (P1-P3 and P3-P1), and 3) walking on three spots (P1, P2 and P3). The walkers were asked to walk at two different paces (normal: 1.8 s^{-1} and very slow pace: 1 s^{-1}) to investigate whether walking paces might affect IACC. Sound recordings were performed in the receiving room using a binaural head equipped with half-inch microphones (Type 40HL, GRAS) and an ambisonic microphone (AMBEO VR MIC, Sennheiser). The sounds were recorded at a sampling rate of 48 kHz and a sampling resolution of 24 bits through the microphones and an AD/DA converter (Motu Ultralite mk3) by a portable recorder (TascamDR-680MKII). As shown in Figure 1b, the microphones were placed at two locations (M1 and M2) in the receiving room, and they were all placed at seated head height (1.27 m from the floor). The receiving room was equipped with sound-absorbing panels to simulate a reverberation time of a typical furnished room (about 0.5 s in the frequency range between 50 and 5k Hz). Background noise level of the receiving room was lower than <25 dB.

Figure 1

For the analyses of the IACC, the durations of most sound recordings were edited as 6 s. Only the recordings of the walking in a straight line at a normal pace were edited as a 5 s clip due to its shorter duration. In the calculation of running IACF, the integration interval 2T was 1 s and the running step was 0.01 s. The IACC values were then averaged for 5 s and 6 s across the walking trajectories. Figure 2 shows several examples of running IACC of the footsteps sounds. For the figure-of-eight walking, the IACC varied significantly along the walking path. In particular, the IACC was lowest when the walker approached the receiver from the sides. On the other hand, the IACC was almost constant for the walking on the spots for both paces. The IACC of walking in a straight line also varied according to the locations of the source and receiver. Overall, for a normal pace walking, the variations of the average IACC values were

0.79-0.89, 0.83-0.91, and 0.87-0.98, respectively, for the figure-of-eight, walking in a straight line and walking on the spot. When the walker was moving at a very slow pace, the average IACC varied between 0.79 and 0.89 for the walking in a figure-of-eight, between 0.70 and 0.93 for the walking in a straight line, and between 0.89 and 0.96 for the walking on the same spot. From the recordings, 51 sound stimuli were chosen considering the average IACC and sound pressure level (SPL, L_{AFmax}). The average IACC and SPL of the selected stimuli for this study are listed in Table 1. The average IACC ranged from 0.41 to 0.93, while L_{AFmax} varied between 45.6 and 62.3 dB. The spectral characteristics of the selected sound stimuli are shown in Figure 3. The frequency characteristics of the sound stimuli used in the current study were similar to those of the sounds that were measured on wooden floors in Japan [45]. A full list of sound stimuli and their IACC and SPL can be found in Supplementary Table S2.

Figure 2

Table 1

Figure 3

2.3. Experimental design

The experiment consisted of two sessions: 1) the evaluation of footsteps sounds at a normal pace with a total of 34 stimuli (Session 1) and 2) the evaluation of footsteps sounds at a very slow pace with 17 stimuli (Session 2). In both sessions, each sound stimulus was presented twice for daytime (i.e., living room with natural light) and night-time conditions (i.e., living room with artificial light). For the day and night-time conditions, 360-degree pictures of a living room with natural or artificial lighting (Figure 4) captured using a camera (GoPro MAX, GoPro) were presented via an HMD (Oculus Rift S, Meta Quest) throughout the experiment.

Figure 4

2.4. Procedure

The experiment took place at the Biomedical Research Institute of the AIST in Osaka, Japan. The participants were provided with a consent form and information sheet upon their arrival and only those who gave their consent participated in the test. After answering some demographic questions and short questionnaires, the participants were invited to familiarise themselves with the virtual interface on the HMD and controllers during a training session. The listening test took place in a sound-proofed room with a low background noise level (<20 dB). The participants sat in a comfortable chair and were asked to answer the questionnaire through the interface presented in the HMD after each stimulus presentation. The stimuli recorded by the ambisonic microphone were reproduced using eight loudspeakers, four at the upper corners of the room (TOA, F-240G), four at the lower corners (Genelec, 8020C), in a cubic configuration by using ambisonic techniques [51]. Low frequency components were compensated with one subwoofer (Velodyne, MicroVee) placed in front of the participants.

As shown in Figure 5, every session consisted of the following sequence, which was repeated for each sound stimulus: 1) the participants were exposed to a 8 s baseline with low background noise and a dark grey screen, 2) the sound stimulus was presented for 8 s with the simulated living room on the HMD, and 3) the participants were given 12 s to rate their annoyance using an 11-point scale (0: ‘not at all’ to 10: ‘extremely’). The duration of sound stimuli in the current experiment (i.e., 8 s) was decided for practical reasons to cover the full path along the floor sample installed in the laboratory, where footsteps were recorded. The stimuli length was also similar to those adopted in previous studies on subjective evaluation of sounds, including research on the annoyance provoked by environmental sounds [52-55]. Paulsen [56] also confirmed that different durations of sound stimuli varying from 1 s to 80 s had little impact on annoyance ratings of highway and white noises. There were breaks for the participants between sessions to avoid fatigue and loss of. All sound sources in each session and sessions were randomised across participants to avoid order effects.

Figure 5

2.5. Data analysis

A MATLAB interface was used to analyse IACC of footsteps sounds. Statistical analyses were performed using SPSS for Windows (version 26, SPSS Inc. Chicago, IL). Pearson's correlation coefficients were computed between 1) annoyance ratings and physical proprieties of sound stimuli (i.e., IACC, L_{AFmax}) and 2) annoyance ratings and participants' noise sensitivity, attitude towards neighbours and chronotypes. Analysis of variance (ANOVA) was used to investigate the effects of spatiality and levels of footsteps on annoyance ratings. Multiple regression analysis was introduced to investigate the extent to which IACC and SPL's affected annoyance ratings. Independent samples *t*-tests were conducted to estimate the significance of the differences in annoyance ratings between 1) footsteps at different paces, 2) daytime and night-time conditions, 3) low and high noise sensitivity groups, and 4) negative and positive attitude towards neighbours groups. Non-parametric Mann-Whitney U test was used to assess the difference in annoyance ratings between E-type and M-type participants because the data in each group were not normally distributed.

3. Results

3.1. Effect of IACC and SPL on annoyance

The annoyance ratings for an adult walking at a normal pace are presented in Figure 6 as a function of IACC and SPL. As shown in Figure 6(a), overall, the annoyance ratings increased together with IACC. More specifically, annoyance ratings ranged between 3.4 ± 1.2 and 9.5 ± 0.5 for IACC in the region of 0.42 and 0.93. The Pearson correlation coefficients between the IACC and the annoyance ratings were significant (r=.332, p<0.01). Analysis of variance (ANOVA) was used to estimate the significance of differences in annoyance ratings across

IACC. For this analysis, and to allow and facilitate future comparisons with the study on the effect of IACC on annoyance, the 68 stimuli (34 stimuli × 2 (lighting conditions)) in Session 1 were grouped into three clusters based on their IACC values: Group 1 with IACC ranging between 0.42 and 0.72 (22 stimuli), Group 2 with IACC ranging between 0.72 and 0.79 (24 stimuli), and Group 3 with IACC varying between 0.79 and 0.93 (22 stimuli). IACC had a significant effect on annoyance ratings: [F (2,3090) = 135.681, (p<0.01)]. A *post-hoc* test confirmed that annoyance ratings of stimuli belonging to Group 1 were significantly lower than those in Groups 2 and 3, while the stimuli in Group 2 were significantly less annoying than those in Group 3.

As shown in Figure 6(b), the annoyance ratings also increased with an increase of SPL. The correlation coefficient between annoyance ratings and SPL was significant (r=.421, p<0.01). A stepwise multiple linear regression analysis was then conducted to assess the effects of IACC and SPL on annoyance ratings. The model in equation 1 was statistically significant [F (2,3090) = 417.4, p<0.01] and the adjusted coefficient of determination (R^2) was 0.231. A low coefficient of determination indicates that there are additional variables that might affect annoyance ratings. Despite the relatively low R^2, this model still fits the data satisfactorily and the R^2 of this model is between the moderate effect size [57]. The standardised partial regression coefficients of IACC and SPL in equation 1 were 0.135 and 0.376, respectively, and these coefficients were statistically significant (p<0.01 for both). This indicates that greater IACC and SPL resulted in greater annoyance ratings. Although the contribution of SPL on annoyance was larger than that of IACC, the influence of IACC on annoyance was still significant.

$$\text{Annoyance} \approx f(\text{IACC}) + f(\text{SPL}) \approx a(\text{IACC}) + b(\text{SPL}) \qquad (1)$$

Figure 6

Further analyses were carried out to see whether there are differences in annoyance ratings between daytime and night-time. Overall, a significant difference between annoyance ratings collected in the two conditions was identified by *t*-test ($p<0.01$). More precisely, annoyance ratings during nighttime conditions were higher compared to the ones acquired during the daytime presentation. The IACC values had significant correlations with the annoyance ratings in both daytime ($r=.346$, $p<0.01$) and night-time conditions ($r=.319$, $p<0.01$). ANOVA also showed that IACC had a significant effect on annoyance ratings in daytime and night-time: [F (2,1566) = 78.883, ($p<0.01$)] for daytime conditions, and [F (2,1521) = 58.348, ($p<0.01$)] for nighttime conditions. In both cases, *post-hoc* tests confirmed significant differences among the three IACC groups: Group 1 provoked significantly lower annoyance than Group 2, which was also significantly less annoyed than Group 3 for both day and nighttime conditions.

3.2. Effect of the pace of the walker on annoyance

Comparisons were made between normal pace (1.8 s^{-1}) and very slow pace (1.0 s^{-1}) to understand the effect of the pace of the walker on annoyance ratings. Annoyance ratings for the two different walking paces are plotted in Figure 7 as a function of IACC, along with their linear regression lines. The regression lines are distinguishable when annoyance ratings are plotted as a function of IACC (Figure 7(a)), whereas they coincide when annoyance ratings are plotted as a function of SPL (Figure 7(b)). This suggests that the different walking paces affected IACC values. However, this was not the case for the SPL. For both paces, the annoyance ratings were significantly correlated with the IACC ($r=.328$ for normal pace and $r=.332$ for very slow pace, $p<0.01$ for both), and with the SPL ($r=.468$ for normal pace and $r=.328$ for very slow pace, $p<0.01$ for both). Fisher's r-to-z transformation was computed to test the significance of differences between the correlation coefficients [58]. It was revealed that the correlation coefficients between annoyance ratings and SPL for the normal and very slow paces were significantly different ($z=6.819$, $p<0.01$), whereas the correlation coefficient between annoyance ratings and IACC for the two walking paces were not significantly different ($z=-0.144$, $p=0.443$). Overall, the annoyance ratings for footsteps sounds at a very slow pace were higher than those at a normal pace and the *t*-test showed that the difference between them was significant ($p<0.01$). Similar findings were found even in daytime and night-time conditions and the *t*-tests confirmed that footsteps sound induced by a very slow pace led to greater annoyance ratings than the sounds at a normal pace ($p<0.01$ for both conditions).

Figure 7

3.3. Effect of non-acoustic factors on annoyance

Several non-acoustic factors were considered as moderators variables affecting the relationships between annoyance ratings and IACC and SPL. They include noise sensitivity, attitude towards neighbours and circadian rhythm type. In this section, all stimuli presented in Sessions 1 and 2 were considered together. First, the overall score of the NoiSeQ-R questionnaire was used to differentiate between low and high noise-sensitivity groups. All the participants who scored below or equal to the median value (11) were classified into the low-noise sensitivity group, while the high noise sensitivity group included all the participants who scored above 11. Accordingly, the low noise-sensitivity group was composed of 24 participants (mean age 23.7 years, SD: 4.9), and the high noise-sensitivity group had 22 participants (mean age 23.6 years, SD 1.8). Figure 8 represents the average annoyance ratings for the two groups regarding IACC and SPL. Overall, the high noise-sensitivity group reported greater annoyance than the low noise-sensitivity group. The *t*-test revealed that the annoyance ratings reported by the high noise-sensitivity group were significantly greater than those of the less sensitive group (*p*<0.01). Similar tendencies were found in both daytime and night-time conditions (*p*<0.01 for both).

Figure 8

Second, the influence of attitude towards neighbours who make noise on the relationships between IACC/ SPL and annoyance ratings was assessed. The participants were divided into two groups according to their overall score calculated from five items: a negative attitude towards neighbours group (those who scored below or equal to the median value) and a positive attitude towards neighbours group (those who scored above the median value). The negative attitude towards neighbours group was composed by 22 participants (mean age 22.8 years, SD 2.4), while the positive attitude towards neighbours group was composed by 24 participants (mean age 22.9 years, SD 4.6). The averaged annoyance ratings for the two groups are shown in Figure 9. Overall, the participants with a negative attitude towards their neighbours who make noise were more annoyed than those who showed a positive attitude towards them. Pearson correlation coefficients between the overall score of the attitude towards neighbours and annoyance ratings were then computed for all the sound sources (*r*=-.126, *p*<0.01), sources in daytime (*r*=-.093, *p*<0.01) and night-time conditions (*r*=-.163, *p*<0.01). The correlation coefficients were all negative, indicating that the better the attitude towards neighbours, the lower the annoyance ratings. For assessing the significance of the difference in annoyance ratings between the two groups, *t*-tests were conducted, and the differences were all significant (*p*<0.01 for all the sound stimuli and the night-time condition; *p*<0.05 for daytime condition). These findings suggest that attitude towards neighbours may be playing a greater role in the annoyance ratings of footsteps sounds during night-time compared to those heard during daytime.

Figure 9

Overall scores of the shortened MEQ questionnaire were calculated for assessing the chronotypes of participants. Participants who scored between 19 and 27 were classified as definite or moderate morning type (M-type, *N*=11), while those who scored between 13 and 18 were classified as intermediate type (D-type, *N*=25). Lastly, participants with a score in the region of 5 and 12 were classified as definite or moderate evening types (E-type, *N*=10). Among these three groups, two distinct groups (M-type and E-type) were compared. The M-type group was composed of ten participants (mean age 24.5 years, SD 6.9), while 11 participants were classified into the E-type group (mean age 23.3 years, SD 2.8). As shown in Figure 10, E-type participants reported greater annoyance ratings than M-type participants. A non-parametric Mann-Whitney U test confirmed that the difference in annoyance ratings for the two types of participants was significant (p<0.01). The differences between the two groups became smaller as IACC and SPLs increased. The Pearson correlation coefficients between the MEQ questionnaire score and annoyance ratings were quite small but still significant (r=-.058, p<0.01 for all stimuli; r=-.068, p<0.01 for daytime; r=-.048, p<0.01 for night-time).

Figure 10

4. Discussion

4.1. Effect of IACC on annoyance

Previous studies have investigated the effects of spatial features of footsteps sounds on subjective evaluation [7, 11-14, 59]. Following previous research on heavyweight concrete buildings [7, 11, 12, 14, 59], our findings support the idea that spatial factors (i.e., IACC) significantly affect annoyance caused by footsteps sounds even in wooden structures. However, this result is not consistent with previous research [13] which suggested that sound source localisation did not have a significant effect on the annoyance level of footfall noise. This may be due to the different sound stimuli and floor structures used in both studies. Brunskog, et al. [13] generated footsteps sound using a binaural impulse response from room acoustic software (Odeon) and a woman walking in high heels on a hard surface with dominant energy at high frequencies. In addition, they assumed that the footsteps sounds were heard from a single-layered lightweight structure. On the other hand, in the present study, the footsteps sounds were recorded under more realistic conditions, using a typical timber joist floor while walking barefoot. Therefore, the high-frequency contents of the footsteps sounds were greatly attenuated and sound energies at low frequencies were dominant.

Furthermore, it was observed that greater IACC (i.e., clearer localisation of the sound source) resulted in greater annoyance ratings. However, Jeon, et al. [11] previously reported the opposite findings in which the annoyance ratings of single impact sounds produced by a rubber ball on heavyweight floors increased with decreasing IACC. This inconsistency may be explained by means of impact source and source locations. Jeon, et al. [11] recorded floor impact sounds by dropping a rubber ball at a centre of the room while the binaural head was also located at the centre of the receiving room. Thus, the variations in IACC were mainly due to sound insulation treatment and room acoustic conditions rather than different walking paths. Also, they calculated the average IACC of the single impact of the rubber ball for an initial 0.5 s. In contrast, different walking paths were considered with two different receiver positions in this study; thus, IACC was mainly influenced by walking paths. Furthermore, in the present study, IACC values were averaged for whole durations of walking (i.e., 5 s and 6 s) which led to greater IACC than in the previous study [11]. However, this study focused on walking barefoot (quite typical for indoor residential spaces) but other impact sounds, such as walking with footwear, could be investigated in the future. Interestingly, the aircraft noise during take-off and landing, which means the noise source moves, with higher IACC was perceived to be more annoying [60].

4.2. Effect of walking pace on annoyance

Consistent with prior literature [16, 17], this research found that the pace of the walker affects annoyance ratings provoked by footsteps sound. Ljunggren, et al. [17] suggested that the impact sound is often barely audible for walking at a normal speed but it quickly becomes very disturbing as soon as the walking speed increases on lightweight floors. Simmons, et al. [16] also highlighted that even a slight increase in walking speed (i.e., in impact force) changes the sound from barely audible to very unpleasant. The present study, however, found an opposite tendency, whereby footsteps sounds at a very low pace are more annoying than footsteps at a normal pace, suggesting that the relation between walking speed and annoyance caused by footsteps sounds is not straightforward (i.e., an increase in walking speed does not necessarily cause an increase in annoyance). Other psychological factors may play an important role in the perception of the footsteps of neighbours at different walking speeds. For example, one may perceive a very slow walking pace as suspicious and stimulate one’s attention and imagery. Most sounds from neighbours are not visually identifiable so they can be classified as acousmatic sounds. Acousmatic sounds are commonly used in theatre and movies to attract the audience’s attention by making them wonder what is generating the sound [61]. Similarly, residents of high-rise wooden buildings may imagine neighbours’ activities while hearing the noise they are making, such as footsteps sounds and unusual walking rates (e.g., very slow speed), which may induce a sense of diffidence. This could be accentuated when residents are relaxing as low activity intensity makes people more sensitive to the acoustic environment, especially when noise is generated by human activity [62].

4.3. Effect of daytime and night-time conditions on annoyance

Several studies have suggested that the time of the day influences the perception of noise as a situational factor [22, 23, 63, 64]. According to Höger [22], higher susceptibility to aircraft noise can be expected in the evening (≈ 18:00-22:00), at night (≈ 22:00-06:00), and in the early morning (≈ 06:00–08:00). These times of day are associated with aural communication as well as recreation and sleep, which are prone to be disturbed or interrupted by noisy events [23]. Other studies [63, 64] have also identified a significant but small increase in annoyance ratings caused by aviation noise in the evening and early morning. Peris, et al. [65] examined the effect of time of the day on annoyance caused by train vibrations in residential areas and found that annoyance was greater during the evening and night-time periods. This study extended the previous research on exposure to other sound sources [22, 23, 63, 64] by confirming that the time of the day, at which footsteps sounds are heard, has an impact on the perceived annoyance. In the present study, annoyance ratings during night-time conditions were higher than the ones obtained during the daytime. This might also be because participants expect a quieter acoustic environment at night than daytime.

In this research, daytime and night-time conditions were simulated using an HMD presenting a 360-degree picture of a living room. This approach is rapidly spreading in the acoustics field with the rise of VR technologies for immersive spaces [14, 66-71]. This technology has been more effective than traditional monitor presentation in psycho-physiological recovery generated by the audio-visual presentation of urban and natural scenery [72] and can be used as an ecologically valid tool in soundscape or noise assessments [73]. The use of the HMD was also validated in an indoor environment where footsteps sounds from neighbours are heard in apartments [14]. However, the lack of senses involved in the simulated environments was also discussed since VR only stimulates visual and auditory senses [74]. Additionally, wearing an HMD affected the spatial quality of sounds by modifying the HRTF [75]. Thus, the simulated conditions used in the experiment could be improved for the generation of a more immersive and familiar environment in future studies.

4.4. Effect of non-acoustic factors on annoyance

Several personal and social non-acoustic factors were introduced in the current research, and they include noise sensitivity, chronotype, and attitudes toward neighbours. Noise sensitivity’s critical role in the subjective evaluation of sounds has been recognised by existing research [24-29]. For instance, Ryu and Jeon [25] found that noise sensitivity significantly influenced the annoyance caused by indoor noise in residential buildings. More recently, Park, et al. [26] declared significant differences in annoyance caused by footsteps sounds in heavyweight concrete buildings between low and high noise-sensitivity groups. Similar results were obtained recently from an experiment using impact sounds produced by a rubber ball on different floor structures, reporting that the high noise-sensitivity group showed a steeper change in their subjective responses than the low noise-sensitivity group [76]. Consistent with the previous literature, this study also found that annoyance ratings from low noise-sensitivity group were significantly lower than those from the high noise-sensitivity group for both daytime and night-time conditions.

Auditory chronobiology is a new discipline of research, which draws attention to the important association of circadian rhythms with hearing. Circadian rhythms control several bodily functions such as sleep, metabolism, and hormone secretion, as well as immune response and auditory functions [32]. Until recently, it was unknown that sensitivity to noise varies at different times of the day [77]. Basinou, et al. [33] investigated the circadian regulation of auditory function and highlighted that night noise trauma is more damaging than day noise trauma. Cederroth, et al. [34] collected the accumulating experimental evidence that the peripheral and central auditory system is under circadian regulation and proposed that circadian aspects should be given greater attention in the auditory field. Thus, in the current study, the chronotype of participants was assessed as an exploratory factor and it had a significant impact on annoyance ratings. Particularly, E-type participants reported significantly higher annoyance than M-type participants for both simulated day and night-time conditions. This finding is consistent with previous studies in which nocturnal types influenced psychological reactions and behaviours. Mecacci and Rocchetti [78] demonstrated that nocturnal types showed more frequent and intense psychological and stress-bound disorders than diurnal types. Achilles [79] also reported that nocturnal types had more difficulties in social adaptation which may affect their perception of neighbour noise. However, the effect of circadian rhythm on annoyance provoked by everyday sounds has not been yet fully investigated; hence, it is necessary to extend this research with more diverse sound sources.

Attitude towards sound source is also identified as playing a key role in mediating annoyance caused by neighbour sounds [35, 36]. Benz, et al. [36] identified several factors affecting neighbour noise annoyance, such as satisfaction with the neighbourhood, relationship with neighbours, residential satisfaction, and noise sensitivity. Park, et al. [35] recently found that a negative attitude towards neighbours weakened the positive relationship between annoyance and coping behaviour. They also suggested that promoting relationships between neighbours could solve conflicts arising from floor impact noise in apartment buildings. Our study confirmed a significant difference in annoyance ratings between participants with a negative or positive attitude towards neighbours. Specifically, those who expressed a negative attitude towards neighbours had higher annoyance than participants with a positive attitude towards neighbours when they were exposed to footsteps sounds. Additionally, the overall scores of the attitude towards neighbour questionnaire significantly correlated (r= -.388, p<0.01) with the scores of the NoiSeQ-R noise sensitivity questionnaire. The negative correlation coefficient suggests that people who were less sensitive to noise showed a better attitude towards neighbours. However, it is still unclear whether noise sensitivity affects attitude or vice versa. Even in a previous investigation [35] that reported the effect of attitude towards neighbours on the relationship between annoyance and coping behaviour, a direct correlation between noise sensitivity and attitude towards neighbours was not found. In addition, attitude towards neighbours showed a positive relationship with circadian rhythm (r=0.289, p<0.01), while the correlation between noise sensitivity and circadian rhythm was negative (r=-0.234, p<0.01). It is not clear how these relationships were developed and how they worked in reaction to footsteps sounds. Therefore, future studies could investigate in more detail the inter-relationships between these non-acoustic factors through a qualitative process of research interviews.

4.5. Limitations and suggestions for future research

There are several limitations to consider in the present study. First, the effect of IACC on annoyance ratings was tested using ANOVA. For this analysis, the sound stimuli with different IACC values were categorised into three groups and different intervals were used to allow similar numbers of sound stimuli in each group. In the first group, IACC varied between 0.42 and 0.72, while IACC ranged between 0.79 and 0.93 in the third group. In both the first and third groups, the ranges of IACC were greater than 0.13, which is a just noticeable difference (JND) of IACC for an impact ball sound [11]. But IACC in the second group had a smaller range than the JND, varying from 0.72 to 0.79. However, the JND was obtained from the experiment using a single impact sound produced by an impact ball so it is not clear if the JNDs of human walking and impact ball sounds would be similar. In the future, thus, it is necessary to determine the JND of IACC for real impact sounds.

Second, the sound stimuli used in the present study were selected from a large set of sound recordings with different walking paths. Although it was found that both IACC and SPL influenced annoyance, their effect sizes could not be computed. Instead, in a previous study [11], small samples of sound stimuli were selected to calculate the contributions of IACC and

SPL to noise annoyance. For instance, three levels of IACC and SPL were chosen while spectral characteristics of the sounds were fixed. Thus, an additional study could be designed with small sets of sounds with fixed intervals of IACC and SPL to validate the findings of this study.

Third, there were a limited number of participants in each circadian rhythm type. Thus, in future studies, it may be helpful to deepen the understanding of the effect of morningness-eveningness on the evaluation of everyday sounds with a larger pool of participants.

Fourth, there are additional parameters that might affect annoyance ratings such as frequency characteristics and amplitude modulations. Thus, further analyses are required to investigate the perception of footsteps sounds by using sound quality metrics and autocorrelation function (ACF) parameters.

5. Conclusion

The current investigation seeks to examine the effect of walking paths on annoyance of footsteps sounds made by upstairs neighbours. It also aimed to see whether non-acoustic variables might have moderating impacts on annoyance. The sound stimuli were the recordings of footsteps over three walking paths (i.e., figure-of-eight, straight, and walking on the spot) and two walking speeds (i.e., very slow and normal). The sound stimuli were characterised by using IACC and SPL (L_{AFmax}). The averaged IACC for 5 s - 6 s varied from 0.41 to 0.93, while the SPL ranged between 45.6 and 62.3 dB. It was found that IACC significantly affected annoyance ratings. More specifically, the sound stimuli with higher IACC were rated more annoying than those with lower IACC. This indicates that clearer localisation of the sound sources led to greater annoyance ratings when upstairs neighbours walked across the floor. The pace of the walker was found to have a significant effect on annoyance ratings. The results showed that footsteps at a very slow pace were rated more annoying than footsteps at a normal pace. In addition, significant differences in annoyance ratings were found between footsteps sounds presented in simulated daytime and night-time conditions. More explicitly, participants assessed footsteps sounds at night more annoying than footsteps sounds with a visual image of the daytime living room. Three non-acoustic factors (noise sensitivity, attitude towards neighbours, and chronotype) were introduced to examine their moderating effects on annoyance. All of them had a significant effect on annoyance ratings. First, the high noise-sensitivity group exhibited higher annoyance ratings than the low noise-sensitivity group. Second, the participants with a negative attitude towards neighbours expressed higher annoyance than those who had a positive attitude towards neighbours. Third, the E-type (evening type) participants rated footsteps sounds more annoying than the M-type (morning type) group. The findings indicate that the spatial characteristics of footsteps sounds from upstairs neighbours should be accounted for in an accurate subjective evaluation of timber floor structures along with temporal features. It is also suggested that, in the future, the effects of chronotype on annoyance can be expanded to everyday sounds.

Acknowledgements

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 721536. This work was partially supported by a Grant-in-Aid for Scientific Research (B) (Grant No. 18H03324) from the Japan Society for the Promotion of Science.

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Table 1. The average IACC and SPL of the selected sound stimuli; FOE stands for 'Figure-of-Eight', WSL stands for 'Walking in Straight Line', and WS stands for 'Walking on Spot'.

	Min IACC	Max IACC	Std IACC	Min L_{AFmax}	Max L_{AFmax}	No. stimuli
			Normal pace of the walker			
FOE	0.42	0.85	0.09	45.7	60.4	12
WSL	0.71	0.93	0.09	47.8	58.6	12
WOS	0.61	0.91	0.04	49.6	62.3	10
			Very slow pace of the walker			
FOE	0.41	0.78	0.10	45.6	56.0	6
WSL	0.48	0.74	0.12	48.9	53.4	6
WOS	0.61	0.83	0.06	52.4	59.1	5

Figure captions

Figure 1. Building acoustics laboratory: a) source room (ceiling height: 2.9 m) with indications of the walking trajectories on the floor sample (figure-of-eight, walking in straight line and walking on spot in P1, P2 and P3) and b) receiving room (ceiling height: 2.6 m) with indications of the microphone positions M1 and M2.

Figure 2. Examples of IACC variations of footsteps sounds at a normal pace (top) and a very slow pace (bottom): figure-of-eight (left), walking on spot (middle), and walking in straight line (right).

Figure 3. Frequency characteristics of footsteps sounds at a normal pace (top) and a very slow pace (bottom): figure-of-eight (left), walking on spot (middle) and walking in straight line (right).

Figure 4. 360° pictures of the living room presented through the HMD: a) daytime condition (natural lighting) and b) night-time condition (artificial lighting).

Figure 5. Outline of the listening test and each stimulus presentation.

Figure 6. Annoyance ratings as a function of IACC (a) and SPL (b). The dashed lines are calculated regressions for all the participants.

Figure 7. Annoyance ratings from footsteps at a normal and a very slow pace as a function of IACC (a) and SPL (b). Linear regression models were fitted on separate data; normal pace (black) and very slow pace (grey).

Figure 8. Annoyance ratings of the low and high noise sensitive groups as a function of IACC (a) and SPL (b). Linear regression models were fitted on separate data; high noise sensitivity group (black line) and low noise-sensitive group (grey line).

Figure 9. Annoyance ratings of the positive and negative attitude towards neighbours groups as a function of IACC (a) and SPL (b). Linear regression models were fitted on separate data; negative attitude towards neighbours group (black) and positive attitude towards neighbours group (grey).

Figure 10. Annoyance ratings of the E-type and M-type participants as a function of IACC (a) and SPL (b). Linear regression models were fitted on separate data; E-type (black) and M-type (grey).