‘Annoyance provoked by single and combined sound sources from neighbours in wooden residential buildings

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Abstract

This study aimed to understand the annoyance provoked by the combination of impact and airborne sound sources from neighbours in wooden residential buildings. Footsteps (adult walking and child running), corresponding to noise from upstairs, were selected as impact sources. Music and speech from side dwellings were also chosen as airborne sound sources. A listening test was then performed on a group of adults who were asked to evaluate annoyance using an 11-point scale. During the experiment, participants were exposed to two different conditions: (1) combined sounds (i.e., footsteps sound in combination with music or speech) and (2) individual sounds. The results showed that total annoyance ratings were affected by impact and airborne sound insulation of floors and partition walls and types of airborne sound sources. In particular, the airborne sound sources from side dwellings played a greater role in the total annoyance when impact sound insulation of the floor was poor. Perceptual models yielded better results in predicting the total annoyance ratings compared to physical models. Among the perceptual models, the mixed model was the best predictor for the impact and airborne sound sources. Overall noise sensitivity score from 35 items did not have a significant moderation effect on the total annoyance ratings, but the moderation effects of two subscales ('work' and 'habitation') were significant.

1. Introduction

Training towards sustainability in the construction industry is promoting the use of wood as raw, renewable, and lightweight material, as an alternative to traditional heavyweight concrete and steel. However, the choice of a lightweight building technique for a more sustainable environment may affect the acoustic comfort of residents because it is not necessarily acoustically sustainable. For instance, Bard et al. [1] reported that the residents in timber buildings are still exposed to various noises from their neighbours including impact noise. This is quite similar to heavyweight multi-storey residential buildings in which residents are frequently exposed to impact sounds caused by upstairs neighbours as well as airborne sounds transmitted from side units [2]. The exposures to neighbour noise negatively impact the occupants, causing stress and reducing the quality of well-being in their home [3, 4]. In particular, the residents are often exposed to multiple sounds from their neighbours at once, leading to more sever influences of the perceived noise.

Transportation noise in combination has been studied extensively by focusing on road traffic, railway, and aircraft noise [5-15]. Specifically, total annoyance due to combination of transportation noise has been widely investigated through socio-acoustic surveys [9-14, 16-20] and laboratory experiments [19, 21-27]. Other noise sources have also been investigated in relation to total annoyance mostly along with transportation noise. They were impulsive sounds from gunfire [22], construction noise such as pile driving and jack hammering [23], industrial noise [24, 25, 28] and community noise including DIY (do-it-yourself) noise [26]. Recently, soundscape studies have also examined the combination of different wanted and unwanted sounds in outdoor environments. Jeon et al. [27] investigated perception of the noise (road traffic and construction) combined with water sounds in a laboratory setting. Similarly, Leung et al. [29] reported that the quality of the acoustical environment could be improved by adding water sounds to road traffic noises at high levels. Other studies also explored preference scores of road traffic noise in combination with water sounds [30, 31] and bird songs [32]. Although many studies have investigated a broad range of sound sources that are heard in a typical living room, there is still a gap in knowledge regarding the effect of combined sound sources caused by neighbours in residential buildings. Using social survey, Jeon et al. [33] investigated overall dissatisfaction with indoor sounds environment due to impact, airborne, drainage and traffic noise; however, the respondents lived in heavyweight buildings.

Due to the intrinsic difference in nature, propagation, and frequency content of impact and airborne sounds, current national building regulations specify requirements concerning airborne and impact sound insulation separately [34]. Impact sound transmission has been measured by using standard impact sources such as tapping machine and impact ball [35, 36], while the airborne sound transmission is quantified using standardised sound signals [37, 38]. In addition, impact and airborne sound transmissions were also predicted individually mainly for independent assemblies of floors or walls [39-41]. However, residents are often exposed to a combination of impact and airborne sounds in multi-storey lightweight buildings. A further investigation on the annoyance provoked by impact and airborne interaction might offer a new instrument for the development of a future holistic building acoustics regulation able to better guarantee satisfactory indoor soundscapes. Hence, it is necessary to investigate how people react to multiple sounds transmitted via floors and partition walls in wooden residential buildings.

Previous research on combined sound sources has developed several models to predict total annoyance. Some of the models are based on ‘physical’ information of the source with independent variables constructed from the source’s sound pressure levels. These include the energy summation model [6], which assumes that individuals mentally integrate the sound levels from different sources as the basis for making overall annoyance judgements. This model was criticised mainly because of its assumption that the relationship between annoyance and total noise exposure is not dependent on the relative contributions of the separate sources to the total noise level. Subsequently, several attempts have been made to take into account the relative contributions of the combined sound sources, leading to the energy difference model [6], the independent effect model [6], the response summation [42, 43], the summation inhibition [44] and the weighted summation model, which resembles the toxic equivalents models [22]. On the other hand, there are models based on ‘perceptual’ information with independent variables constructed from mean partial annoyance ratings. These include the dominance model [23], which does not work correctly for cases where the difference in annoyance between dominant and non-dominant sources is limited. The linear regression model [26] attempted to differentiate between the sources by describing the global annoyance as a weighted sum, but was criticised for its absence of an underlying perceptual cognitive theory. The vector summation model [23], adopted from other sensory fields such as perceived intensity of odours [45] and binocular brightness [46], predicted loudness summation fairly well for soft sounds (40 dB attenuation compared to louder), but overestimated louder ones (110 dB). The mixed model [24, 47] is based on the absolute difference between the partial annoyance ratings by considering the possible interaction between the noises. Recent research on annoyance from combined sound sources suggests that perceptual models work better [7, 8, 20, 24]. than physical based models. However, it is not clear whether the above-mentioned models might work for different contexts such as indoor environment. Besides, it is well known that the total annoyance caused by combined sources is affected by non-acoustic as well as acoustic factors. For example, noise sensitivity is regarded as an essential variable in understanding subjective responses to environmental noise [48-52] and building noise such as floor impact sounds in apartment buildings [53, 54]. Recently has been remarked that other than acoustical properties like sound pressure levels, personality traits (including noise sensitivity) exert considerable influences on the maximum likelihoods of prediction models and thus should not be excluded from the model specification form [29]. Consequently, some studies on environmental noise investigated a moderation effect of noise sensitivity on total annoyance [9, 12, 14, 18, 24, 28, 29] but none of those included indoor soundscape comprising neighbour noise**.** Therefore, it is needed to quantify the total annoyance caused by neighbour noise in timber buildings, to explore which of the existing models are appropriate to predict total annoyance and to assess whether noise sensitivity might have an influence on perception of combined sounds in indoor situations.

The present study aimed to investigate the annoyance provoked by neighbour noise in lightweight residential buildings. A laboratory experiment was performed in an audiometric booth with neighbour noise from upstairs and side dwellings. Footsteps sounds were chosen as a structure-borne sound transmitted from the upstairs, while speech and music were chosen as airborne sounds from side dwellings. It was first hypothesised that the annoyance of neighbour noise might be different across impact and airborne sound insulation of the building elements. Thus, all the sound stimuli were filtered to represent different impact and airborne sound insulation of partition walls and floors in lightweight buildings. It was also hypothesised that total annoyance might be affected by different combinations of structure-borne and airborne sources; thus, participants rated the annoyance of individual and combined sound sources. Lastly, it was assumed that noise sensitivity might affect annoyance ratings of individual and combined sources. The noise sensitivity of the participants was assessed using the Noise Sensitivity Questionnaire (NoiSeQ) [55].

2. Methodology

2.1. Participants

The study was ethically approved by the School of the Arts Committee on Research Ethics at the University of Liverpool. A total of 41 healthy adults with self-reported normal hearing (21 males and 20 females) was recruited and took part in the experiment. The participants ranged in age from 20 to 40 (median= 28 and std=4.4). Participants were then divided into two groups based on the median noise sensitivity score (median=58 and std=11.4) obtained from the NoiSeQ to explore the moderation effect of noise sensitivity on annoyance. Twenty-one participants were classified into ‘low noise sensitive group’ (median=52 and std=9), while 20 were classified into ‘high noise sensitivity group’ (median=65 and std=5.3).

2.2. Sound stimuli

Four different sound sources were selected as representative of impact and airborne sounds which are most frequently heard in residential buildings as reported in previous studies [2, 56-60]. Adults walking and child running were reported as the most frequently heard structure-borne noise sources in apartment buildings, while voices and music contributed to most of the complaints on airborne noise [2, 56, 61-64]. Thus, two impact sources were selected: footsteps (an adult walking at two different paces; normal (1.8 s^{-1}) and fast (2.2 s^{-1})) and a child running. The two paces of the walker were included based on findings of a previous study in wooden structures which suggested that the speed of walking has a substantial effect on the annoyance [65]. The other two are airborne sources from neighbours: speech (conversation between two people) and music (a piece of classical music played on the piano). Among various music types, a piece of classical piano was chosen because it has more energies at high frequencies. It was assumed that the combinations of low (i.e., impact sources) and high frequency sounds (speech and classical piano) might lead to greater total annoyance. Impact sounds were recorded in the acoustics laboratory, where a lightweight timber joists floor separates the vertically adjacent source and receiving rooms [66]. In order to simulate the reverberation time of a furnished dwelling, sound-absorbing panels were placed in the receiving room and the measured reverberation time was about 0.5 s in the frequency range between 50 and 5 k Hz. Sound recordings were carried out with four different floor 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, suspended ceiling and floating floor. Floor structures 2-4 are commonly used in residential buildings in European countries. Floor structure 2 is a commonly used timber joist floor for detached houses which reduces impact sound and flanking transmission, while floor structure 3 is an alternative structure to the single floating floor solution to increase impact sound insulation and considerably reduce the height of the room underneath. Also, floor structure 4 is a typical floor construction in European countries to achieve a good value of impact sound insulation in residential buildings. The basic structure (i.e., floor structure 1) is not relevant for residential buildings but selected with others to represent the worst condition. A female adult (50 kg and 1.65 m tall) and a five-year-old child (22 kg) were chosen as walkers. A binaural head equipped with two half-inch microphones (Type 40HL, GRAS) [67] was used to record footsteps sounds in the receiving room while adult and child walked or ran diagonally in the source room. Figure 1 shows the A-weighted maximum sound pressure levels (L_{AFmax}) of the selected impact sounds in the frequency range between 31.5 Hz and 1000 Hz. Most sound stimuli had dominant sound energies at low frequencies below 100 Hz. However, several sounds also showed strong sound energies at high frequencies because those were recorded on floor without a floating floor system installed or carpet which is effective for sound reduction at high frequencies.

Figure 1

The airborne sounds (i.e., speech and music) were anechoic recordings. To simulate attenuation due to partitions, three lightweight partitions with good, medium, and poor airborne sound insulation performances were applied to the recordings. The weighted sound reduction indices (R_{w}) of the three simulated partitions were 52, 43 and 33 dB, respectively. The schematic representation of the lightweight partitions and weighted sound reduction indices characterising each partition can be found in the Supplement Figure S1. The poor sound reduction index (R_{w}=33) is not commonly used in a dividing wall between different households, but it was included to represent the worst situation. Frequency characteristics of the filtered airborne sounds are plotted in Figure 2. The spectral characteristics of the airborne sounds were adjusted using the graphic equaliser of Audition 3.0 (Adobe). The frequency characteristics of impact and airborne sound sources without A-weighting can be found in the Supplement Figure S2 in which impact sound sources are expressed in terms of L_{Fmax} and airborne sound sources are expressed in terms of L_{eq}.

Figure 2

2.3. Experimental design

The experiment consisted of two parts: the evaluation of individual sounds and the evaluation of combined sounds. In the first part, the annoyance to individual sounds (footsteps, speech, and music) was assessed and total annoyance caused by footsteps combined with speech or music was evaluated in the second part. Combinations with footsteps sounds and speech or music are expressed below as F_{Adult}+S, F_{Child}+S, F_{Adult}+M and F_{Child}+M for the sake of convenience. The adult walking sounds recorded from four different configurations ranged between 27 dB and 56 dB in terms of L_{AFmax}, while the child running recorded from three configurations (floor structures 1, 3 and 4) showed a smaller range from 33 dB to 51 dB (L_{AFmax}). Thus, as listed in Table 1, the L_{AFmax} of the adult walking varied from 30 to 55 dB with an interval of 5 dB, while the child running's L_{AFmax} varied from 35 dB to 50 dB. The ranges of sound pressure levels (SPL) were also determined based on the previous study [66], reporting the ranges in SPLs of real impact sources in wooden floors. It was assumed that A-weighted equivalent sound pressure level (L_{Aeq}) of the speech and music were 79 and 80 dB in the neighbour's houses [61]; thus, the ranges in L_{Aeq} of the filtered speech and music sounds were slightly different. The filtered speech and music sounds varied from 24 to 42 dB and from 25 dB to 44 dB, respectively, in terms of L_{Aeq}. Sound stimuli in different SPLs were selected from the recordings with different configurations to avoid additional spectral adjustments. For example, the adult walking (normal pace) at 50 and 55 dB were the recording from the bare timber joists with chipboard on top with and without carpet, while the adult walking at 30 and 35 dB were the recording from the bare timber joists and chipboard equipped with floating floor and suspended ceiling system finished with carpet. Intermediate levels of L_{AFmax} of 40 and 45 dB were recorded on the floor equipped with floating floor and suspended ceiling.

Table 1

2.4. Procedure

The experiment took place in an audiometric booth with low background noise level. Participants were sitting on a comfy chair and asked to answer a questionnaire through a graphic user interface (GUI) in Visual Basic 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 ambient noise in the living room. The experiment was composed of four sessions (one individual sound session and three combined sound sessions). Each sound stimulus was presented for 20 seconds with a picture of a living room on the monitor and 10 seconds were given to participants to rate annoyance answering to the question 'Assuming that you are exposed to noise at home, what number from 0 to 10 best shows how much you are annoyed by noise (0: '*Not at all'* and 10: '*Extremely*')'. The question was based on the previous studies on the annoyance of environment and neighbour noise in laboratory settings [28, 68, 69]. There were breaks between sessions to avoid excessive fatigue and loss of concentration for the participants. In the individual sound session, impact and airborne sound sources were presented for 15 minutes, while, in the remaining sessions, the impact sound combined with airborne sound sources were presented for 21 minutes each. All sound sources and sessions were randomised across participants to avoid order effects. Before the starting of the experiment, participants were asked to answer the 35-items questionnaire (NoiSeQ) [55] to assess their noise sensitivity. A training session of five minutes was also designed to help participants to familiarise with the sound stimuli and questionnaire form. During the experiments, participants were asked to imagine relaxing in their own home while sounds were coming from neighbouring units.

2.5. Statistical analyses

Statistical analyses were performed using SPSS for Windows (version 26, SPSS Inc. Chicago, IL). Analysis of variance (ANOVA) was used to investigate the effects of footsteps type and levels on annoyance. Independent samples *t*-tests were conducted to estimate the significance of the difference in annoyance ratings firstly, between source types at each sound level considered and secondly, between every sound pressure level step for each sound source. The distribution of the data of the low and high noise-sensitivity groups was not normal; thus, non-parametric test was carried out. Kruskal-Wallis test for the differences between two noise-sensitivity groups was used. Pearson correlation coefficients were calculated at first between annoyance ratings and sound pressure levels, afterwards between annoyance ratings of adult's footsteps, psychoacoustics metrics and L_{AFmax}. Multiple regression analysis was introduced to assess the goodness-of-fit of the existing total annoyance models.

3. Results

3.1. Annoyance from single sound sources

The results of the annoyance ratings of the single sound sources are presented in Figure 3. Overall, for impact sounds, the annoyance ratings increased with the sound pressure levels except for the adult's footsteps at 45 dB. The Pearson correlation coefficients between the SPLs and annoyance ratings were all significant (r=0.73, p<0.01 for adult walking at a normal pace; r=0.64, p<0.01 for adult walking at a fast pace; r=0.61, p<0.01 for child running). The airborne sounds showed different tendencies across source types. Annoyance ratings for speech were not much changed with varying SPLs (r=-0.08, p=0.39), whereas the annoyance ratings for music increased with increasing of L_{Aeq} (r=0.31, p<0.01).

Analysis of variance (ANOVA) was used to estimate the significance of differences in annoyance ratings across source levels and type of sound sources. The levels of sound sources had a significant effect on annoyance ratings for all impact sounds: [F (5,238) = 60.313, (p < 0.01)] for adult walking at a normal pace, [F (5,240) = 44.062, (p < 0.01)] for adult walking at a fast pace, [F (3,159) = 32.599, (p < 0.01)] for child running, and for the music clip [F (2,120) = 6.299, (p < 0.01)]. Levels did not have a significant effect on annoyance ratings for speech [F (2,120) = 0.588, (p = 0.56)]. Footsteps type (adults walking at two paces and child running) had a significant effect on annoyance ratings of impact sources [F (2,650) = 7.907, (p < 0.01)]. Similarly, airborne source type (music and speech) had a significant effect on annoyance ratings [F (1,244) = 42.303, (p < 0.01)].

A series of independent samples *t*-tests was carried out to assess the significance of differences in annoyance rating between neighbouring SPLs. For the impact sounds, the annoyance ratings were significantly increased compared to the neighbouring SPLs except for 40 and 45 dB for the adult's footsteps at normal pace and 35 and 40 dB for the child running. For the airborne sources, annoyance ratings for speech did not show significant differences either between good and medium partition or between medium and poor partition. Annoyance ratings for music showed no significant difference between good and medium partition, but a significant difference was found between medium and poor partition (p<0.05).

Additional independent samples *t*-tests were then carried out to assess the significance of difference across sound source type at each SPL. As reported in Figure 3, the differences between adult walking at 1.8 and 2.2 s^{-1} were not significant, except at 50 dB (p<0.01). The differences between adult walking and child running were not consistent; significant at 35, 40 and 50 dB and insignificant at 30, 45 and 55 dB. For the airborne sounds, the difference between annoyance ratings for speech and music were statistically significant (p<0.01) when the partition wall was characterised by good (R_w=52 dB) and medium (R_w=43 dB) airborne sound insulation. But the difference between them was not significant for the poor sound reduction index (R_w=33).

Figure 3

The inconsistency in annoyance ratings with varying SPLs may be related to the selected sound stimuli recorded from different floors. The sound stimuli at the same level were not always from the same floor so their frequency characteristics may differ for source types (more details can be found in the Supplement Figure S3). As shown in Figure 1, adult walking sounds at 40 dB showed much greater energies in the range between 250 Hz and 1 kHz than those at 45 dB due to the presence of the carpet. Therefore, psychoacoustic metrics were introduced, assuming that these would be helpful to understand annoyance ratings of the adult walking sounds with different spectral contents. BK connect (Brüel & Kjær) was used to calculate *loudness*, *sharpness*, *roughness* and *fluctuation strength*. *Loudness* was calculated according to ISO 532-1, which describes the procedures for calculating the time-varying *loudness*. Also, the percentile loudness N5 (the loudness value reached or exceeded in 5% of the measurement time) was computed. During the calculation of *sharpness*, *roughness* and *fluctuation strength*, the time interval between the spectra was set at 2 ms. The results of the psychoacoustic parameters are listed in Annex Table A1. The adult walking sounds at 40 dB showed much greater *sharpness* than others due to the strong sound energies at mid and high frequencies. Pearson correlation coefficients were calculated between psychoacoustic metrics, L_{AFmax} and annoyance ratings. All the metrics and L_{AFmax} were significantly correlated with annoyance ratings of footsteps sounds ($p<0.01$ for all). Among them, L_{AFmax} showed the highest correlation coefficients with the averaged annoyance ratings ($r=0.953$), followed by *loudness* ($r=0.922$) and N5 ($r=0.918$). Even a combination of *loudness* and *sharpness* obtained from the linear regression analysis ($r=0.905$, $p<0.01$) was not better than a sole L_{AFmax}. The correlation coefficients across the participants are listed in Supplement Table S2.

3.2. Total annoyance from impact and airborne sources

The total annoyance ratings for impacts sounds in combination with the airborne sounds are presented in Figure 4. The differences between the adult walking at different paces were not statistically significant; thus, the annoyance ratings of adult walking combined with airborne sounds were averaged across the paces. The annoyance ratings caused by adult walking and child running in isolation are plotted as references. In general, as shown in Figures 4(a) and 4(b), the total annoyance ratings of footsteps sound combined with speech were different from the ratings of footsteps sounds in isolation, whereas the ratings of footsteps sounds were not much changed even after additions of music (Figures 4(c) and 4(d)). Specifically, for impact sounds in combinations with speech, the total annoyance ratings varied across the sound insulating performance of the partitions. When impact sound insulation of the floor was poor (i.e., impact sound levels at 50-55 dB), the contributions of addition of speech to the total annoyance were negligible. On the other hand, for the floors with impact sound levels of 30-35 dB (good impact sound insulation), the total annoyance ratings significantly increased with additions of speech transmitted through partition walls with a medium (R_w=43 dB) or poor (R_w=33 dB) airborne sound insulation. This is because the speech from a medium or poor wall was more annoying than the single impact sources. The additions of speech transmitted through a partition wall with the highest sound reduction index (R_w=52 dB) did not lead to a significant change in the annoyance ratings except for the child running at 30 dB. Different tendencies were found in combinations of impact sounds with music. Significant differences between the total annoyance and single noise sources were found only in two cases with the lowest SPLs of adult walking and child running. In addition, the sound reduction index of the partition walls had little effect on the total annoyance ratings for both adult walking and child running. Means and standard deviations of annoyance ratings for single and combined sound sources can be found in the Supplement Table S3.

Figure 4

3.3. Prediction of total annoyance

From literature, a total of eight total annoyance models were selected: 1) the energy summation model [6], 2) the energy difference model [6], 3) the independent effect model [6], 4) the weighted summation model [22], 5) the dominance model [23], 6) the linear regression model [26], 7) the vector summation model [23] and 8) the mixed model [24]. The first four models are ‘physical’ and the other four are ‘perceptual’ models. Linear regression analyses were performed for the above mentioned eight models with total annoyance ratings (A_T) as a dependent variable and the SPLs (for psychophysical models) and annoyance ratings of single sound sources (for perceptual models) as independent variables. For the weighted summation model [22], the impact sound sources were considered as the reference source and a series of iteration showed that the best goodness-of-fit was achieved from k=17. For the vector summation model [23], an angle α = 96° allowed the model to be optimised. Table 2 shows the results of regression analyses performed for the assessment of the total annoyance models in terms of goodness-of-fit. The higher the determination coefficient (R^2) and the lower the standard error of the estimate (std. err.) indicate the better the goodness-of-fit of the model. Overall, perceptual models showed higher determinations coefficients than those of the physical models. Among the physical models, the weighted summation model with k=17 showed the best goodness-of-fit with a determination coefficient of 0.551 and a standard error 1.392, while, among the perceptual models, the mixed model showed the highest determination coefficient of 0.760 and the lowest standard error of 1.017. More details can be found in the Supplement Figure S4 where the linear regressions between predicted and measured annoyance ratings across total annoyance models.

Table 2

3.4. Effects of noise sensitivity on annoyance

The NoiSeQ questionnaire [55] has question items in five subscales (‘leisure’, ‘work’, ‘habitation’, ‘communication’, and ‘sleep’) and the overall noise sensitivity score is calculated as the summation of each subscale score. In the present study, both the overall and the subscale scores were used because the use of the subscale scores was previously reviewed and validated [70]. First, a series of Kruskal-Wallis tests was conducted between the low and high noise sensitivity groups to determine the effect of the self-assessed global noise sensitivity score on annoyance of single sounds. The majority of the differences between the two groups were not significant for both impact and airborne sound sources. Only one significant difference was found at 45 dB for the child running (p<0.05). Similarly, the differences in total annoyance ratings between two noise sensitivity groups were assessed through Kruskal-Wallis tests and there was no significant difference for the combinations (F+S and F+M). Secondly, the effects of the subscale scores on the annoyance ratings were investigated. The participants were divided into low and high noise sensitivity groups according to median values in each subscale in Figure 5 (‘leisure’ median=10, std=3.1; ‘work’ median=14, std=3.5; ‘habitation’ median=12, std=3.1; ‘communication’ median=11, std=3.2; ‘sleep’ median=10, std=4.7) and the analysis was then repeated using non-parametric Kruskal-Wallis tests. Overall, many significant differences were found in the subscales ‘work’ and ‘habitation’, whereas significant differences were rarely found in other subscales (‘leisure’, ‘communication’ and ‘sleep’). More specifically, in the subscale ‘work’, significant differences were identified ($p<0.05$) for all the single footsteps sounds (F_{Adult} and F_{Child}), all the single speech sounds through medium and poor partitions, 21 out of 36 combinations of F_{Adult}+S and F_{Adult}+M and 15 out of 24 combinations of F_{Child}+S and F_{Child}+M. Also, in the subscale ‘habitation’, significant differences were found ($p<0.05$) for some single footsteps sounds (F_{Adult}at 35 dB and F_{Child} at 30 and 35 dB), all the speech sound through medium and poor partitions, eight out of 36 combinations of F_{Adult}+S and F_{Adult}+M and 12 out of 24 combinations of F_{Child}+S and F_{Child}+M. For the other subscales, three significant differences were found in the ‘communication’ but there were no differences in the ‘leisure’ and ‘sleep’. More details are listed in Annex Table A4.

Figure 5

4. Discussions

4.1. Annoyance of individual sounds

Previous studies [71-73] have reported strong relationships between SPLs and annoyance of footsteps sounds in lightweight structures. Annoyance ratings caused by footsteps were significantly correlated with standardised single-number quantities (e.g., $L_{n,w}$, $L_{n,w}$+$C_{I,50-2500}$, $L_{n,w} + C_{I,20-2500}$, etc.); however, frequency characteristics of sound stimuli used in the listening test were not presented [71, 72]. A previous study from Ljunggren et al. [74] also demonstrated significant relationships between annoyance and single-number quantities from field survey, reporting information on spectral characteristics of common impact sounds such as adult walking, dropping of a toy and moving of a chair. The present study confirmed and further expanded their finding by using more various sound sources with varying frequency characteristics. For instance, child running and adult walking at two different speeds were introduced as the sound stimuli. In addition, the sound stimuli were selected from the recordings with different floors. The annoyance ratings of adult walking and child running in isolation were highly correlated with the SPLs. The annoyance ratings of this study can be comparable to those obtained from footsteps recorded in other lightweight floors. Previous research [71-73]. highlighted how annoyance caused by similar sound sources (e.g., footsteps) vary greatly when considering various wooden structures and this was confirmed by our findings. For wooden structures with floating floor installed annoyance span between 1 and 6.5 on an 11-point scale in [72] similarly to our results. Gover et al., [71] investigated 14 different lightweight floor assemblies including some very similar to the one used in this study (e.g., NRC-15 and floor structure 3) and reported a variation in annoyance ratings similar to the ones presented in this paper. If compared to annoyance ratings obtained when footsteps were recorded in heavyweight building the present ratings look higher. In particular, Park et al. [68] reported the annoyance ratings of an adult walking at 40, 50 and 60 dB (L_{AFmax}) and they were much lower than those of adult walking sounds in this study. This may be because of the difference in frequency characteristics transmitted through lightweight timber floors and heavyweight concrete structures. This indicates that the choice of a lightweight building technique may lead to higher annoyance compared to a heavyweight concrete structure for impact sounds with similar L_{AFmax}. Other studies also confirmed that annoyance ratings of impact sounds (including footsteps, rattling, or tinkling and scraping) heard through timber floor and cross-laminated timber floor assemblies, were more annoying than those in heavyweight concrete floors [72-74].

The present study revealed that annoyance ratings of speech sounds were not affected by airborne sound insulation of the partition wall (r=-0.08, p>0.05). This was not consistent with other studies [61, 75], reporting that annoyance of speech sounds decreased with increasing sound reduction index R_{w}. This disagreement may be explained by the speech sounds used in the laboratory experiment. In previous studies, the speech sounds were Harvard sentences, which were unintelligible [61] and overlapping voices [75]. On the other hand, the conversation clip used in the present study was intelligible, especially for the sounds presented through the medium and poor performing partitions. However, for the speech sounds heard through the partition with good airborne sound insulation (R_{w}=43 dB), the annoyance ratings were similar to those of previous studies [61, 75]. In this study, the annoyance ratings provoked by the music clip were lower than those in previous studies in which music sounds were presented through partitions with similar sound reduction indices [61, 75]. This inconsistency may be due to the different genres and styles of music used in the experiments. Compared to the classical piano clip in the present study, the previous studies used rap, house and pop music [61], and music with a strong bass component [75]. This implies that the classical piano music from the neighbours is less annoying than other music sounds in a residential setting. Another study [63] investigated several music samples including classical music excerpts such as ‘Fauré: quartet for piano and strings’ with 12 different airborne sound insulation curves; however, the direct comparison with the present study is not available. Thus, it is necessary to compare residents’ reactions to various music clips from their neighbours in the future.

Several studies [61, 75] highlighted the differences in annoyance ratings caused by speech and music. For example, Park and Bradley [61] investigated annoyance of three Harvard sentences (phonetically balanced and with low predictability) and three music clips (rap, house, and pop music) presented through twenty different partitions. They reported that the music clips were more annoying than the speech and this is not consistent with the findings of the present study in which speech was rated as more annoying than music from neighbours. This may be because the speech and music sounds used in the present study are quite different from those in previous studies. This result indicates that the types of airborne sounds from neighbours and degree of speech intelligibility play an important role in the perceived annoyance. Furthermore, previous studies [76-78] have also reported that the speech with higher intelligibility was more annoying than less intelligible speech. But it is still not known about the effect of speech intelligibility of neighbour’s noise on annoyance in living room; thus, this could be further studied in the future.

4.2. Annoyance of combined sounds

Many studies [22, 23, 27] in community noise have reported that total annoyance ratings of combined noises are influenced by the SPLs of individual noises. Berglund et al. [23] demonstrated that the total annoyance was less than the arithmetic sum of the annoyance and more than the arithmetic mean of the annoyance of the individual sounds. Jeon et al. [27] also showed that the total annoyance of road traffic combined with construction noise was much greater than the annoyance of single construction noise, but the differences between them became smaller with increasing SPLs of construction noise in isolation. Similarly, the differences between the total annoyance of road traffic in combination with gunshot noise and the annoyance of gunshot noises in isolation decreased with increasing SPLs of gunshot noise [22]. In addition, Vos [22] demonstrated the changes in the total annoyance of two construction noises in relation to the SPLs of the single construction noise. The present study confirmed that the differences between the total annoyance of footsteps sounds combined with speech and the individual annoyance of the footsteps sounds were different across the SPLs of the footsteps sounds. For the partitions with poor and medium airborne sound insulation, the total annoyance was significantly greater than the annoyance of individual footsteps sounds at low SPLs, whereas both total annoyance and the annoyance of single footsteps sounds were similar at high SPLs. However, there was little difference between the total annoyance and single annoyance for the partitions with R_w=52 dB because the SPLs of the airborne noises were very low. Moreover, for the combinations of the footsteps sounds with music, the total annoyance ratings were similar to the annoyance ratings of individual sounds for all the partitions. This is because the music was much less annoying than the speech sounds; thus, the contribution of the music to the total annoyance was minor. This implies that the additional neighbour noises with low SPLs and less annoying did not have a significant impact on the total annoyance.

4.3. Prediction models of total annoyance

The present study revealed that the perceptual models are better than the physical models in terms of their goodness-of-fit. This result shows a good agreement with the previous studies [8, 20, 24, 28], reporting that perceptual models had higher R^2 values than the physical models in predicting the total annoyance of combined environmental noises. However, the best fit models within the perceptual models were slightly different across the previous studies. Klein et al. [8] demonstrated that four perceptual models (dominance, vector summation, linear regression and mixed models) showed very high R^2 values above 0.94, while the R^2 values of the dominance, vector summation and mixed models were slightly higher than that of the linear regression model in another study [24]. More recently, Marquis-Favre and Morel [28] suggested that the vector summation, linear regression and mixed models are slightly better than the dominance model. In the present study, all the perceptual models showed similar fits although the R^2 values were slightly lower than those in the previous studies [8, 24, 28].

Among the physical models, in the present study, the weighted summation model yielded the best result with a higher R^2 value than other models. Similarly to the perceptual models, the best models and R^2 value were slightly different across the previous studies [6, 7, 22, 24, 28]. In general, the experimental studies showed better predictions than field studies. For example, Taylor [6] reported that the energy difference model showed the best quality in predicting the total annoyance and R^2 values were lower than 0.6. In contrast, another field study [7] showed that the best model fit was obtained from the dominance model with a much higher R^2 value than other physical models. The variations in the best fit modes can be explained by the differences in the noise environments such as noise level and noise source. For instance, the dominance model shows good prediction when one noise is much more dominant than the other. Perception of impact sounds is more accurately explained by the L_{AFmax} than L_{Aeq}; however, L_{Aeq} was used even for the footsteps sounds to quantify the predictability of the physical models in the present study. Thus, it was expected that the use of L_{Aeq} for the impact sounds might contribute to the lower R^2 values than those in other laboratory experiments [8, 22, 28]. Another reason for the less accurate prediction of the weighted summation model of the current study may be attributed to the variation in the spatial pattern of the sound exposures. In the present study, neighbour sounds were presented through floor (footsteps) and partition walls (speech and music), violating the independence assumption. According to Miedema

[16], total annoyance might be different between the situation with two sources from the same side of a dwelling and the situation with the sources from different sides of the dwelling.

4.4. Effects of noise sensitivity on annoyance

Previous studies have revealed that noise sensitivity is a key factor in mediating the reaction to the annoyance of community noise [51, 79-81] and neighbour sound sources [54, 68, 82]. However, few studies investigated the role of this trait in the assessment of total annoyance from combined sound sources [18, 24, 28]. Marquis-Favre and Morel [28] reported that noise sensitivity had a significant effect on the partial and total annoyance from industrial and road traffic noise, explaining the greatest amount of variance of the annoyance ratings collected during the laboratory experiment. In another laboratory study [24], the global noise sensitivity score calculated from five items was not significantly correlated with total annoyance, but weak correlations were found between the total annoyance and each of five items. Lam et al. [18] also investigated the effect of noise sensitivity on the annoyance of mixed transportation noise by constructing structural equation modelling, but the difference in annoyance between high and low noise sensitivity groups was not significant. This discrepancy could be attributed to the use of different items for assessing noise sensitivity. In the present study, the noise sensitivity was assessed using a 35-item questionnaire [55], whereas other studies used a single question [18, 28] and five questions [24]. In addition, in the present study, significant differences were found between low and high noise sensitivity groups across two subscales (‘work’ and ‘habitation’). More significant differences were identified by the ‘work’ subscale than the ‘habitation’ subscale even though the habitation subscale is closer to the context and sound stimuli used in this research. This might be related to the reliability of the items in each subscale and Sandrock et al. [70] reported that the subscale ‘work’ was more reliable than the subscale ‘habitation’.

4.5. Limitations

There are some limitations to consider in the current study. First, this study focused on the footsteps sounds and airborne sources among diverse neighbour noises but, there are other sources in residential buildings such as the dropping of items or domestic appliances (e.g., washing machine) [2]. Thus, two airborne sources used in the present study were limited to cover all the sources. Furthermore, the number of airborne sounds was less than the impact sounds. Thus, more sound sources, in particular various airborne sources, with wider variation in frequency content, need to be considered in the future. In the present experiment, airborne sound sources were presented as transmitted exclusively from partition wall and impact sound sources as transmitted exclusively from floor. However, several studies [83-86] confirmed that cross transmission of airborne and impact sounds through floor and partition walls can happen in lightweight buildings. In the future, the airborne sounds transmitted through floors and impact sounds transmitted through partition walls could be considered to better represent indoor soundscape of wooden multi-storey buildings. In addition, the very low and single background noise (NC-25) was used in this study. In the future, variation in background noise level could be introduced to explore the masking effects of them on the indoor noise sources. Second, as a laboratory study, this research is related to short-term annoyance assessed in an imaginary situation for short noise sequences, consequently the corresponding judgments represent an annoyance potential [87]. Laboratory conditions are useful to carefully investigate different acoustical factors (e.g., sound level, spectral content, etc.) and their potential interactions for combined noises [28], whereas they are lacking many aspects encountered in real-life situations. Hence, the findings of the current study could be validated by comparing them with a simulated environment experiment or an in-situ survey is more likely to reflect a real situation. Third, the participants were asked to imagine that they were relaxing at home in the daytime without detailed time. However, people’s reaction to sound would be different according to the times of the sonic events. Previously, Park et al. [2] reported that many adult walking noises occurred early in the morning and child running was also heard in the early evening. A study on traffic noise also reported higher annoyance ratings in the evening or early morning than in the daytime [88]. Therefore, it would be necessary to investigate how the residents react to neighbour noises at different times with changes in lighting and activities. Eventually, the present study examined only noise sensitivity among non-acoustic factors despite previous findings that noted the importance of non-acoustic factors such as house ownership and attitudes towards neighbours [53, 82, 89].

4.6. Practical implications

The findings of this study suggest that the partition walls in lightweight buildings should be carefully selected in relation to the impact sound insulation of the floors. This is because the good performing floor (footsteps sounds at 30-35 dB) are not sufficient to ensure good acoustic comfort (i.e., low annoyance) when the residents are exposed to the airborne sounds through the partition walls with a poor airborne sound insulation. For instance, 50% of satisfaction with the combined sound sources (i.e., less than ‘5’ on an 11-point scale) was obtained with footsteps sounds less than 30 dB for a poor performing partition wall (R_w=33 dB). But, for partition walls with medium (R_w=43 dB) and good performances (R_w=52 dB), the footsteps sounds should be less than 40 dB and 45 dB, respectively. It was also found that the footsteps sounds were more annoying than speech and music sounds. Thus, it would be important to have a good performing floor to reduce the total annoyance in wooden residential buildings. Currently, there are separate guidelines on airborne and impact sound insulations; however, the present study implies that the total annoyance is influenced by both the impact and airborne sounds. Therefore, it would be useful to develop a holistic guideline considering all the possible sound sources. This approach has already been applied to indoor soundscape research [90, 91]. Limiting noise and investigating its negative impact are just one facet of the acoustic design aiming at producing pleasurable and comforting acoustics scenarios. Accordingly, the building industry target is recently shifting from designing acceptable acoustics spaces to release buildings that can enhance people’s health and well-being [92, 93]. Hence, understanding human response to indoor acoustic environments comprising multiple sound sources may help in filling the gap between predicted and experienced acoustic performance of built environments. In particular, the present study confirmed that the existing perceptual models are quite accurate to predict the total annoyance of neighbour sounds. Thus, the acoustic comfort in the residential buildings could be assessed based on the total annoyance by considering other non-acoustic factors. This may be especially relevant during the pandemic where many people are isolated and working from home. During the lockdown, people were more frequently exposed to neighbour noise such as talking/shouting and TV/music [94] and complaints about neighbour noise significantly increased in London [95]. Accordingly, indoor soundscape studies offer precious insights on how residents perceive indoor environment while spending more time at their homes.

5. Conclusion

This study set out to assess the total annoyance provoked by neighbours' noise in wooden residential buildings through a listening test. The experiment firstly aimed to determine how annoyance varies across single and combined neighbour noise transmitted through different floor and partition walls. Additionally, it was aimed to assess the existing total annoyance models in terms of their goodness-of-fit for the ratings and to investigate the effect of noise sensitivity on annoyance ratings. The results showed that annoyance ratings of single impact sources were significantly different from those of the impact sources combined with airborne sources. The research also demonstrated that the annoyance ratings of the combined sound sources were influenced by airborne and impact sound insulation performances of both partition walls and floors. More precisely, the airborne sound insulation characteristics of the partition walls have a minor impact on total annoyance with a poor performing floors. On the other hand, the partition wall plays a more important role with good performing floors. Therefore, the partition walls in lightweight buildings should be carefully selected in relation to the impact sound insulation of the floors. Among the total annoyance models, the perceptual models (e.g., dominance, linear regression, vector summation and mixed models) showed a greater goodness-of-fit compared to the physical models (e.g., energy summation, energy difference, independent effect, and weighted summation models). In particular, the mixed model had the best goodness-of-fit considering impact sounds, speech and music. Overall, the noise sensitivity score did not show a significant moderation effect on the annoyance caused by neighbours' sounds heard singularly or in combination. Instead, two subscales (‘work’ and ‘habitation’) showed several significant differences between the two high and low sensitive groups. The findings of this study may contribute to the development of a holistic guideline of the indoor environment considering all the possible sound sources.

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6. References

1. Bard, D., N.G. Vardaxis, and E. Sondergard, *Acoustic Comfort Investigation in Residential Timber Buildings in Sweden.* Journal of Sustainable Architecture and Civil Engineering, 2019. **24**(1): p. 78-89.
2. Park, S.H., P.J. Lee, and B.K. Lee, *Levels and sources of neighbour noise in heavyweight residential buildings in Korea.* Applied Acoustics, 2017. **120**: p. 148-157.
3. Maschke, C. and H. Niemann, *Health effects of annoyance induced by neighbour noise.* Noise Control Engineering Journal, 2007. **55**(3): p. 348-356.
4. Hammersen, F., H. Niemann, and J. Hoebel, *Environmental noise annoyance and mental health in adults: findings from the cross-sectional German Health Update (GEDA) Study 2012.* International journal of environmental research public health, 2016. **13**(10): p. 954.
5. Bottom, C. and D. Waters, *A social survey into annoyance caused by the interaction of aircraft noise and traffic noise.* Journal of Sound and Vibration, 1971. **19**(4): p. p. 473-476.
6. Taylor, S.M., *A comparison of models to predict annoyance reactions to noise from mixed sources.* Journal of Sound and Vibration, 1982. **81**(1): p. 123-138.
7. Nguyen, T., et al., *Comparison of models to predict annoyance from combined noise in Ho Chi Minh City and Hanoi.* Applied Acoustics, 2012. **73**(9): p. 952-959.
8. Klein, A., C. Marquis-Favre, and P. Champelovier, *Assessment of annoyance due to urban road traffic noise combined with tramway noise.* The Journal of the Acoustical Society of America, 2017. **141**(1): p. 231-242.
9. Wothge, J., et al., *The combined effects of aircraft and road traffic noise and aircraft and railway noise on noise annoyance—An analysis in the context of the joint research initiative NORAH.* International Journal of Environmental Research and Public Health, 2017. **14**(8): p. 871.
10. Lercher, P., et al., *Community response to multiple sound sources: Integrating acoustic and contextual approaches in the analysis.* International Journal of Environmental Research and Public Health, 2017. **14**(6): p. 663.
11. Lechner, C., D. Schnaiter, and S. Bose-O’Reilly, *Application of the noise annoyance equivalents model for aircraft, rail and road traffic noise to self-reported sleep disturbance.* Acta Acustica united with Acustica, 2021. **5**: p. 12.
12. Lechner, C., D. Schnaiter, and S. Bose-O’Reilly, *Combined Effects of Aircraft, Rail, and Road Traffic Noise on Total Noise Annoyance—A Cross-Sectional Study in Innsbruck.* International Journal of Environmental Research and Public Health, 2019. **16**(18): p. 3504.

13. Lechner, C., C. Kirisits, and S. Bose-O'Reill, *Combined annoyance response from railroad and road traffic noise in an alpine valley.* Noise and Health, 2020. **22**(104): p. 10.
14. Gille, L.-A., C. Marquis-Favre, and K.-C. Lam, *Partial and total annoyance due to road traffic noise combined with aircraft or railway noise: Structural equation analysis.* International Journal of Environmental Research and Public Health, 2017. **14**(12): p. 1478.
15. Gille, L.-A. and C. Marquis-Favre, *Estimation of field psychoacoustic indices and predictive annoyance models for road traffic noise combined with aircraft noise.* The Journal of the Acoustical Society of America, 2019. **145**(4): p. 2294-2304.
16. Miedema, H., *Relationship between exposure to multiple noise sources and noise annoyance.* The Journal of the Acoustical Society of America, 2004. **116**(2): p. 949-957.
17. Öhrström, E., et al., *Annoyance due to single and combined sound exposure from railway and road traffic.* The Journal of the Acoustical Society of America, 2007. **122**(5): p. 2642-2652.
18. Lam, K.-C., et al., *Annoyance response to mixed transportation noise in Hong Kong.* Applied Acoustics, 2009. **70**(1): p. 1-10.
19. Schäffer, B., et al., *Residential green is associated with reduced annoyance to road traffic and railway noise but increased annoyance to aircraft noise exposure.* Environment International, 2020. **143**: p. 105885.
20. Marquis-Favre, C., L.-A. Gille, and L. Breton, *Combined road traffic, railway and aircraft noise sources: Total noise annoyance model appraisal from field data.* Applied Acoustics, 2021. **180**: p. 108127.
21. Izumi, K., *Annoyance due to mixed source noises—A laboratory study and field surve on the annoyance of road traffic and railroad noise.* Journal of Sound and Vibration, 1988. **127**(3): p. 485-489.
22. Vos, J., *Annoyance caused by simultaneous impulse, road-traffic, and aircraft sounds: A quantitative model.* Journal of the Acoustical Society of America, 1992. **91**(6): p. 3330-3345.
23. Berglund, B., et al., *Loudness (or annoyance) summation of combined community noises.* The Journal of the Acoustical Society of America, 1981. **70**(6): p. 1628-1634.
24. Pierrette, M., 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): p. 178-186.
25. Morel, J., et al., *A laboratory study on total noise annoyance due to combined industrial noises.* Acta Acustica united with Acustica, 2012. **98**(2): p. 286-300.
26. Botteldooren, D. and A. Verkeyn, *Fuzzy models for accumulation of reported community noise annoyance from combined sources.* The Journal of the Acoustical Society of America, 2002. **112**(4): p. 1496-1508.
27. Jeon, J.Y., et al., *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): p. 1357-1366.
28. Marquis-Favre, C. and J. Morel, *A simulated environment experiment on annoyance due to combined road traffic and industrial noises.* International Journal of Environmental Research Public Health, 2015. **12**(7): p. 8413-8433.
29. Leung, T., et al., *Developing a multivariate model for predicting the noise annoyance responses due to combined water sound and road traffic noise exposure.* Applied Acoustics, 2017. **127**: p. 284-291.
30. Jeon, J.Y., et al., *Acoustical characteristics of water sounds for soundscape enhancement in urban open spaces.* The Journal of the Acoustical Society of America, 2012. **131**(3): p. 2101-2109.
31. Chau, C.K., et al., *Modelling noise annoyance responses to combined sound sources and views of sea, road traffic, and mountain greenery.* The Journal of the Acoustical Society of America, 2018. **144**(6): p. 3503-3513.
32. Hong, J.Y. and J.Y. Jeon, *The effects of audio–visual factors on perceptions of environmental noise barrier performance.* Landscape and Urban Planning, 2014. **125**: p. 28-37.
33. Jeon, J.Y., J.K. Ryu, and P.J. Lee, *A quantification model of overall dissatisfaction with indoor noise environment in residential buildings.* Applied Acoustics, 2010. **71**(10): p. 914-921.

34. Rasmussen, B., *Sound insulation between dwellings–Requirements in building regulations in Europe.* Applied Acoustics, 2010. **71**(4): p. 373-385.
35. *ISO 10140-3 Acoustics — Laboratory measurement of sound insulation of building elements — Part 3: Measurement of impact sound insulation.* 2021.
36. *ISO 717-2 Acoustics - Rating of sound insulation in buildings and of building elements - Part 2: Impact sound insulation*. 2020.
37. *ISO 10140-2 Acoustics — Laboratory measurement of sound insulation of building elements — Part 2: Measurement of airborne sound insulation.* 2021.
38. *ISO 717-1 Acoustics — Rating of sound insulation in buildings and of building elements — Part 1: Airborne sound insulation.* 2020.
39. Hopkins, C. and R. Hall, *Impact sound insulation using timber platform floating floors on a concrete floor base.* Building Acoustics, 2006. **13**(4): p. 273-284.
40. Ljunggren, S., *Airborne sound insulation of thick walls.* The Journal of the Acoustical Society of America, 1991. **89**(5): p. 2338-2345.
41. Ljunggren, S., *Airborne sound insulation of thin walls.* The Journal of the Acoustical Society of America, 1991. **89**(5): p. 2324-2337.
42. Ollerhead, J.B. *Predicting public reaction to noise from mixed sources*. in *Internoise* 1978.
43. Ollerhead, J.B. *Accounting for time of day and mixed source effects in the assessment of community noise exposure*. in *Third International Congress on Noise as a Public Health Problem*. 1980.
44. Powell, C.A., *A summation and inhibition model of annoyance response to multiple community noise sources*. 1979: National Aeronautics and Space Administration.
45. Berglund, U. and T. Lindvall, *Psychological processing of odor mixtures.* Psychological Review, 1976. **83**(6): p. 432-441.
46. Rule, S.J., *Binocular processing of brightness information: A vector-sum model.* Journal of Experimental Psychology, 1978. **4**(1): p. 132-143.
47. Morel, J., et al. *Proposal for a simple model predicting the total annoyance due to industrial noises with low-frequency content mixed to industrial noises with a 100Hz main component*. in *Internoise*. 2010.
48. Fields, J.M., *Effect of personal and situational variables on noise annoyance in residential areas.* The Journal of the Acoustical Society of America, 1993. **93**(5): p. 2753-2763.
49. Jakovljevic, B., K. Paunovic, and G. Belojevic, *Road-traffic noise and factors influencing noise annoyance in an urban population.* Environment International, 2009. **35**(3): p. 552-556.
50. Öhrström, E., M. Björkman, and R. Rylander, *Noise annoyance with regard to neurophysiological sensitivity, subjective noise sensitivity and personality variables.* Psychological Medicine, 1988. **18**(3): p. 605-613.
51. Van Kamp, I., et al., *The role of noise sensitivity in the noise–response relation: a comparison of three international airport studies.* The Journal of the Acoustical Society of America, 2004. **116**(6): p. 3471-3479.
52. Job, R., *Community response to noise: A review of factors influencing the relationship between noise exposure and reaction.* The Journal of the Acoustical Society of America, 1988. **83**(3): p. 991-1001.
53. Park, S.H., et al., *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): p. 1158-1167.
54. Park, S.H. and P.J. Lee, *Reaction to floor impact noise in multi-storey residential buildings: The effects of acoustic and non-acoustic factors.* Applied Acoustics, 2019. **150**: p. 268-278.
55. Schutte, M., et al., *The development of the noise sensitivity questionnaire.* Noise Health, 2007. **9**(34): p. 15.
56. Grimwood, C., *Complaints about poor sound insulation between dwellings in England and Wales.* Applied Acoustics, 1997. **52**(3-4): p. 211-223.
57. Bradley, J. *Deriving acceptable values for party wall sound insulation from survey results*. in *Proceedings of Inter-Noise*. 2001. Citeseer.

58. Ryu, J.K. and J.Y. Jeon, *Influence of noise sensitivity on annoyance of indoor and outdoor noises in residential buildings.* Applied Acoustics, 2011. **72**(6): p. 336-340.
59. Jeon, J.Y., et al., *Review of the impact ball in evaluating floor impact sound.* Acta Acustica united with Acustica, 2006. **92**(5): p. 777-786.
60. Rasmussen, B., M. Machimbarrena, and P. Fausti. *Building acoustics throughout Europe. Volume 2: housing and construction types country by country*. 2014. COST Action.
61. Park, H.K. and J.S. Bradley, *Evaluating standard airborne sound insulation measures in terms of annoyance, loudness, and audibility ratings.* The Journal of the Acoustical Society of America, 2009. **126**(1): p. 208-219.
62. Jeong, J.-H., P.-J. Lee, and J.-Y. Jeon. *Questionnaire survey on annoyance of floor impact sound*. in *Proceedings of the Korean Society for Noise and Vibration Engineering Conference*. 2006. The Korean Society for Noise and Vibration Engineering.
63. Vian, J.P., W.F. Danner, and J.W. Bauer, *Assessment of significant acoustical parameters for rating sound insulation of party walls.* The Journal of the Acoustical Society of America, 1983. **73**(4): p. 1236-1243.
64. Bradley, J. *Deriving acceptable values for party wall sound insulation from survey results*. in *the 2001 International Congress and Exhibition on Noise Control Engineering, The Hague, The Netherlands*. 2001. Citeseer.
65. Simmons, C., K. Hagberg, and E. Backman, *Acoustical Performance of Apartment Buildings–Resident's Survey and Field Measurements. AkuLite Report 2*. 2011.
66. Frescura, A., et al., *Correlations between standardised and real impact sound sources in lightweight wooden structures.* Applied Acoustics, 2021. **173**: p. 107690.
67. Einig, J. and U. Schanda. *Binaurales Aufnahmesystem zur Auralisation tieffrequenten Trittschalls*. in *Deutsche Gesellschaft für Akustik e.V. (ed.), Fortschritte der Akustik - DAGA*. 2012.
68. Park, S.H., P.J. Lee, and J.H. Jeong, *Effects of noise sensitivity on psychophysiological responses to building noise.* Building Environment, 2018. **136**: p. 302-311.
69. Park, S.H. and P.J. Lee, *Effects of floor impact noise on psychophysiological responses.* Acta Acustica united with Acustica, 2017. **116**: p. 173-181.
70. Sandrock, S., M. Schutte, and B. Griefahn, *The reliability of the noise sensitivity questionnaire in a cross-national analysis.* Noise and Health, 2007. **9**(34): p. 8.
71. Gover, B.N., et al. *Subjective ranking of footstep and low-frequency impact sounds on lightweight wood-framed floor assemblies*. in *Forum Acusticum*. 2011.
72. Späh, M., et al., *Subjective and objective evaluation of impact noise sources in wooden buildings.* Building Acoustics, 2013. **20**(3): p. 193-213.
73. Ljunggren, F., C. Simmons, and R. Öqvist, *Correlation between sound insulation and occupants' perception–Proposal of alternative single number rating of impact sound, part II.* Applied Acoustics, 2017. **123**: p. 143-151.
74. Ljunggren, F., C. Simmons, and K. Hagberg, *Correlation between sound insulation and occupants' perception–Proposal of alternative single number rating of impact sound.* Applied Acoustics, 2014. **85**: p. 57-68.
75. Pedersen, T.H., S. Antunes, and B. Rasmussen, *Online listening tests on sound insulation of walls: A feasibility study*, in *EURONOISE*. 2012, European Acoustics Association-EAA. p. 1219-1224.
76. Liebl, A., A. Assfalg, and S. Schlittmeier, *The effects of speech intelligibility and temporal–spectral variability on performance and annoyance ratings.* Applied Acoustics, 2016. **110**: p. 170-175.
77. Preis, A., et al., *The relationship between speech intelligibility and the assessment of noise annoyance.* Noise Control Engineering Journal, 2013. **61**(3): p. 255-264.
78. Schlittmeier, S.J. and A. Liebl, *The effects of intelligible irrelevant background speech in offices–cognitive disturbance, annoyance, and solutions.* Facilities, 2015.
79. Heinonen-Guzejev, M., et al., *Self-report of transportation noise exposure, annoyance and noise sensitivity in relation to noise map information.* Journal of Sound and Vibration, 2000. **234**(2): p. 191-206.

80. Stansfeld, S.A., et al., *Road traffic noise, noise sensitivity and psychological disorder.* Psychological Medicine, 1993. **23**(4): p. 977-985.
81. Fyhri, A. and R. Klæboe, *Road traffic noise, sensitivity, annoyance and self-reported health—A structural equation model exercise.* Environment International, 2009. **35**(1): p. 91-97.
82. Park, S.H., P.J. Lee, and J.H. Jeong, *Emotions evoked by exposure to footstep noise in residential buildings.* PloS one, 2018. **13**(8): p. e0202058.
83. Lentzen, S., S. Born-Van Der Jagt, and E. Gerretsen, *Sound-insulation and walking-induced vibration models of lightweight junctions.* Proc. of Euroregio, 2010.
84. Caniato, M., et al., *Acoustic of lightweight timber buildings: A review.* Renewable Sustainable Energy Reviews, 2017. **80**: p. 585-596.
85. Barbaresi, L., et al. *Experimental measurements of flanking transmission in CLT structures*. in *Proceedings of Meetings on Acoustics 22ICA*. 2016. Acoustical Society of America.
86. Morandi, F., et al., *Measurement of flanking transmission for the characterisation and classification of cross laminated timber junctions.* Applied Acoustics, 2018. **141**: p. 213-222.
87. Flindell, I.H., *Community response to multiple noise sources*. 1982, University of Southampton.
88. Philipps-Bertin, C., et al. *Perception and annoyance due to tramway noise*. in *Internoise*. 2007. Institute of Noise Control Engineering.
89. Park, S.H., P.J. Lee, and K.S. Yang, *Perception and reaction to floor impact noise in apartment buildings: a qualitative approach.* Acta Acustica United with Acustica, 2016. **102**(5): p. 902-911.
90. *ISO/TS 12913-2:2018 Acoustics — Soundscape — Part 2: Data collection and reporting requirements* 2018.
91. Torresin, S., et al., *Assessment methods and factors determining positive indoor soundscapes in residential buildings: A systematic review.* Sustainability, 2019. **11**(19): p. 5290.
92. Torresin, S., et al., *Indoor soundscape assessment: A principal components model of acoustic perception in residential buildings.* Building Environment International, 2020. **182**: p. 107152.
93. Altomonte, S., et al., *Ten questions concerning well-being in the built environment.* Building Environment International, 2020. **180**: p. 106949.
94. Lee, P.J. and J.H. Jeong, *Attitudes towards outdoor and neighbour noise during the COVID-19 lockdown: A case study in London.* Sustainable Cities and Society, 2021. **67**: p. 102768.
95. Tong, H., et al., *Increases in noise complaints during the COVID-19 lockdown in Spring 2020: A case study in Greater London, UK.* Science of the Total Environment, 2021. **785**: p. 147213.

Table 1. Sound pressure levels of selected sound stimuli; L_{AFmax} for impact sound sources and L_{Aeq} for airborne sound sources

Source		Overall levels (dB)
Impact	Adult walking at a normal pace	30 – 35 – 40 – 45 – 50 – 55
	Adult walking at a fast pace	30 – 35 – 40 – 45 – 50 – 55
	Child running	35 – 40 – 45 – 50
Airborne	Speech	24 – 29 – 42
	Music	25 – 29 – 44

Table 2. Total annoyance model assessment in terms of goodness-of-fit considering impact sounds, speech, and music. R^2 is the determination coefficient; Std. Err. is the standard error of the estimate; A_T is the total annoyance; L_T is the A-weighted overall sound pressure level; L_{impact} and $L_{airborne}$ are the A-weighted equivalent sound pressure levels of the impact and airborne sound sources respectively; A_{impact} and $A_{airborne}$ are the partial annoyances for the impact and airborne sources, respectively.

Model		Regression Equation	R	R^2 *(adjusted)*	Std. Err.
Physical models	Energy Summation [6]	$A_T = 0.204L_T - 2.192$	0.607	0.368 *(0.362)*	1.652
	Energy Difference [6]	$A_T = 0.215L_T - 0.02\lvert L_{impact} - L_{airborne}\rvert - 2.438$	0.610	0.372 *(0.365)*	1.647
	Independent Effect [6]	$A_T = 0.173L_{impact} + 0.067L_{airborne} - 2.471$	0.642	0.412 *(0.406)*	1.594
	Weighted Summation (k=17) [13]	$A_T = 0.23L_T - 2.87$	0.743	0.551 *(0.547)*	1.392
Perceptual models	Dominance [14]	$A_T = 0.89Max(A_{impact}, A_{airborne}) + 0.91$	0.848	0.718 *(0.715)*	1.103
	Linear Regression [17]	$A_T = 0.69A_{impact} + 0.48A_{airborne} + 0.69$	0.858	0.736 *(0.733)*	1.068
	Vector summation (α=96) [14]	$A_T = 0.14\sqrt{({A_{impact}}^2 + {A_{airborne}}^2 + 2A_{impact}A_{airborne}\cos\alpha)} + 2.93$	0.864	0.746 *(0.744)*	1.047
	Mixed [15]	$A_T = 0.57A_{impact} + 0.58A_{airborne} + 0.23\lvert A_{impact} - A_{airborne}\rvert + 0.34$	0.872	0.760 *(0.758)*	1.017

Figure captions

Figure 1. Frequency characteristics of impact sounds (footsteps) a) adult walking at a normal pace at 30, 35,40,45,50 and 55 dB in terms of L_{AFmax}, b) adult walking at a fast pace at 30, 35,40,45,50 and 55 dB in terms of L_{AFmax} and c) child running at 35,40,45 and 50 dB in terms of L_{AFmax}.

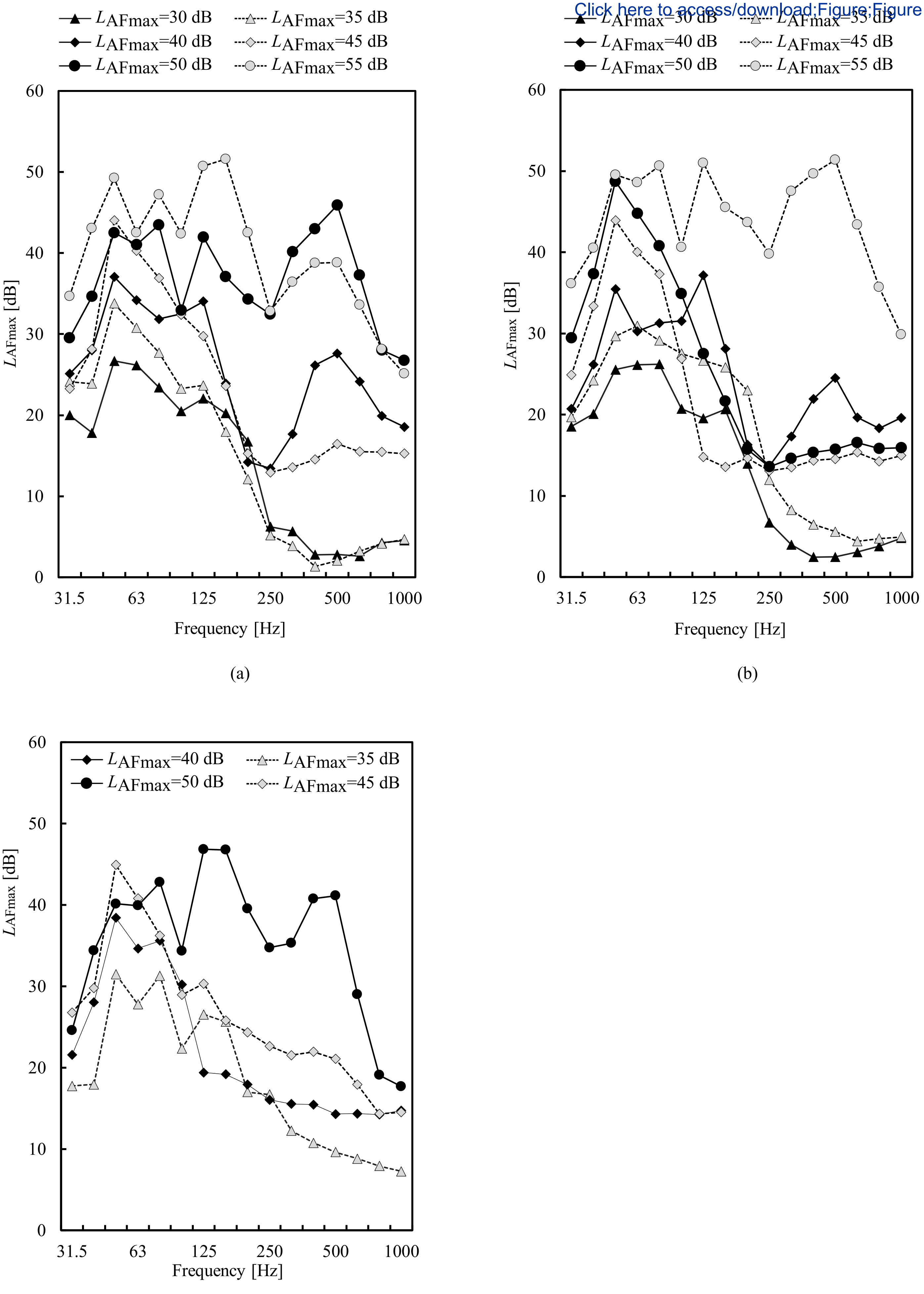
Figure 2. Frequency characteristics of airborne sounds a) speech: indication of the original clip and of the clip after being filtered through partition wall with sound reduction index R_{w}=52 dB, R_{w}=43 dB and R_{w}=33 dB; and b) music: indication of the original clip and of the clip after being filtered through partition wall with sound reduction index R_{w}=52 dB, R_{w}=43 dB and R_{w}=33 dB.

Figure 3. Annoyance ratings for single sounds a) impact sound sources: Adult walking at normal and fast pace and child running; b) airborne sound sources: speech and music.

Figure 4. Total annoyance for footsteps in combination with speech a) $\mathrm{F}_{\mathrm{Adult}}$ + S and b) $\mathrm{F}_{\mathrm{Child}}$ + S. Total annoyance for footsteps in combination with music: c) a $\mathrm{F}_{\mathrm{Adult}}$ + M and d) $\mathrm{F}_{\mathrm{Child}}$ + M. The dotted lines represent the linear regression models for the footsteps sounds in isolation.

Figure 5. Subscale scores of the noise sensitivity questionnaire: leisure, communication, work, habitation, and sleep. The horizontal line dividing upper and lower half of boxplot represents the median.

Figure 1

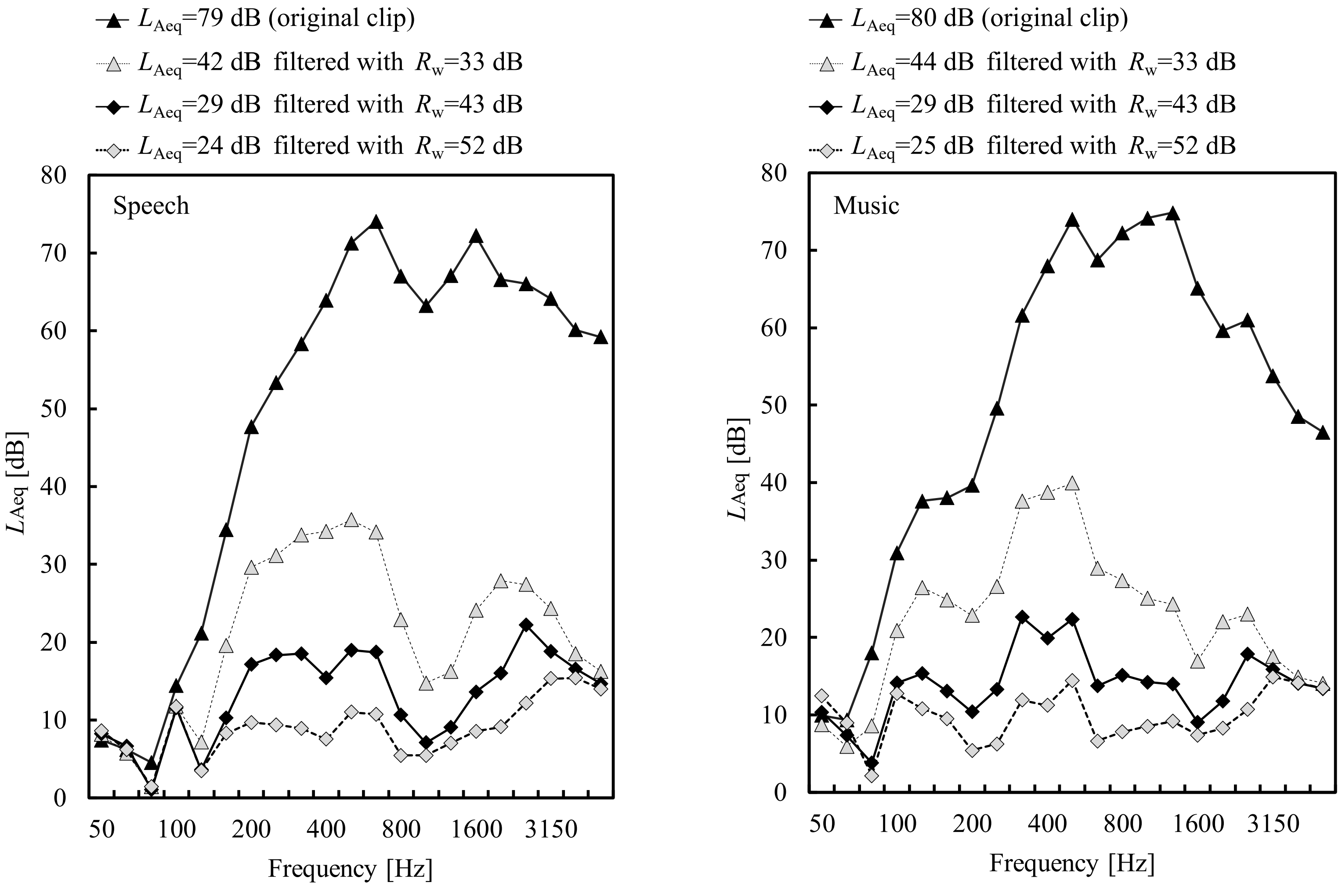

LAFmax=30 dB
LAFmax=35 dB
LAFmax=40 dB
LAFmax=45 dB
LAFmax=50 dB
LAFmax=55 dB
LAFmax [dB]
0
10
20
30
40
50
60
31.5
63
125
250
500
1000
Frequency [Hz]

(a)

(b)

(c)

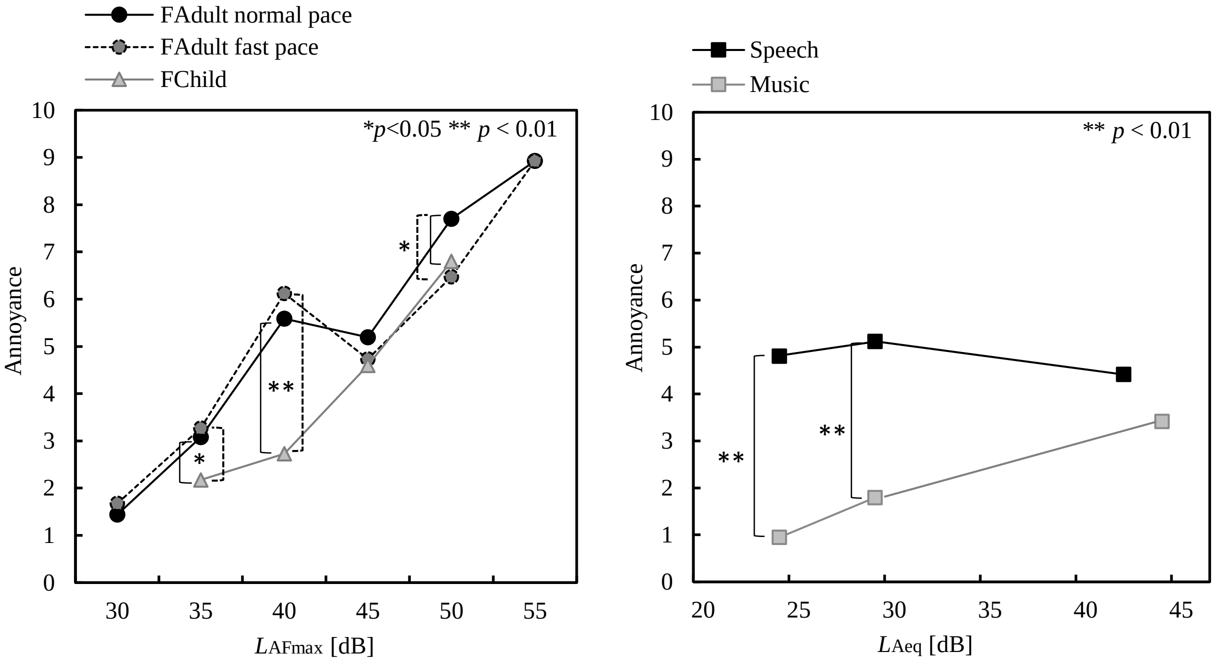
Figure 2


LAeq=79 dB (original clip)
LAeq=42 dB filtered with Rw=33 dB
LAeq=29 dB filtered with Rw=43 dB
LAeq=24 dB filtered with Rw=52 dB
Speech
LAeq [dB]
0
10
20
30
40
50
60
70
80
50
100
200
400
800
1600
3150
Frequency [Hz]
LAeq=80 dB (original clip)
LAeq=44 dB filtered with Rw=33 dB
LAeq=29 dB filtered with Rw=43 dB
LAeq=25 dB filtered with Rw=52 dB
Music
LAeq [dB]
0
10
20
30
40
50
60
70
80
50
100
200
400
800
1600
3150
Frequency [Hz]

(a)

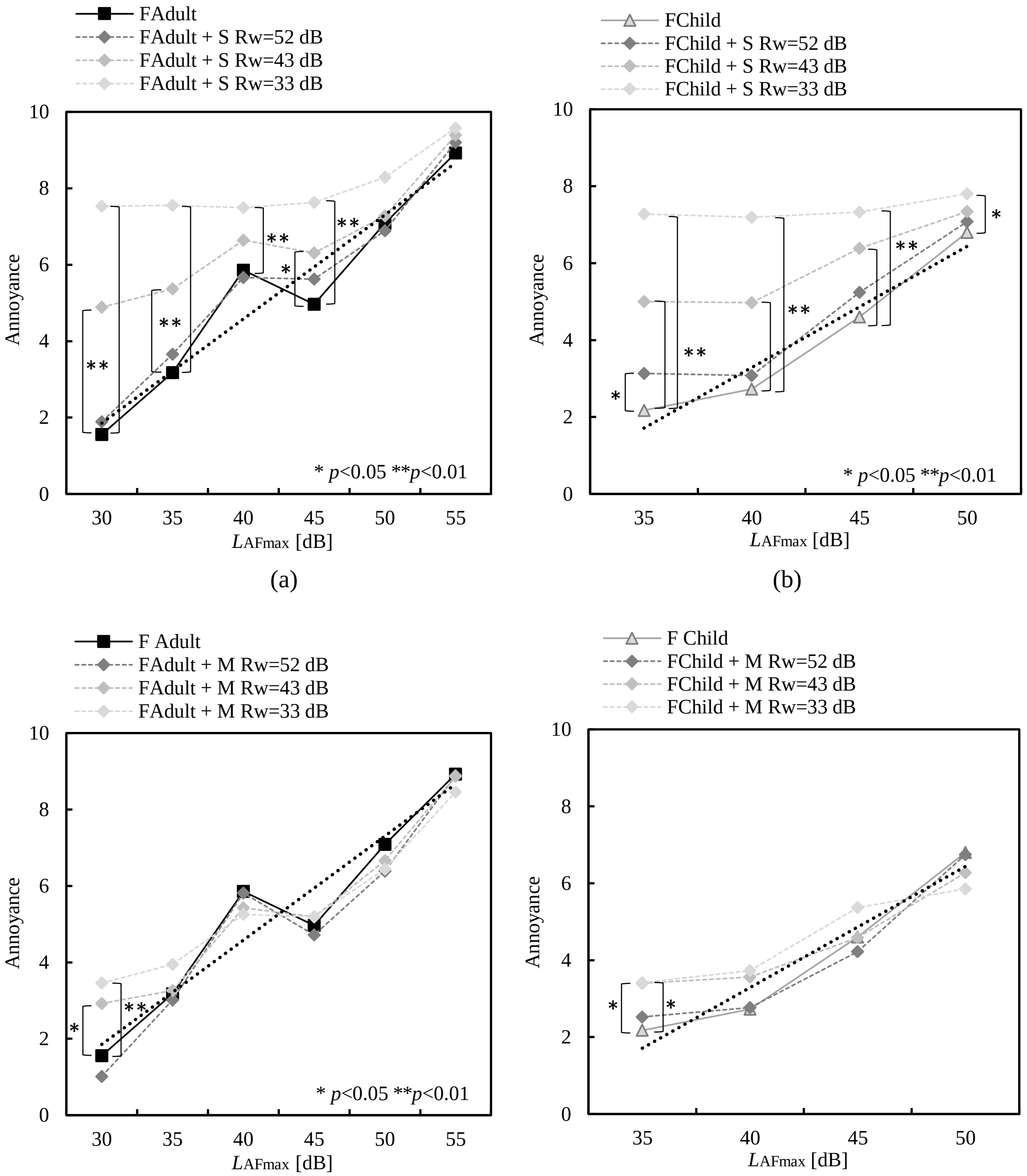
(b)

Figure 3


FAdult normal pace
FAdult fast pace
FChild
*p<0.05 ** p < 0.01
Annoyance
0
1
2
3
4
5
6
7
8
9
10
*
**
*
30
35
40
45
50
55
LAFmax [dB]
Speech
Music
** p < 0.01
Annoyance
0
1
2
3
4
5
6
7
8
9
10
**
**
20
25
30
35
40
45
LAeq [dB]

(a) (b)

Figure 4



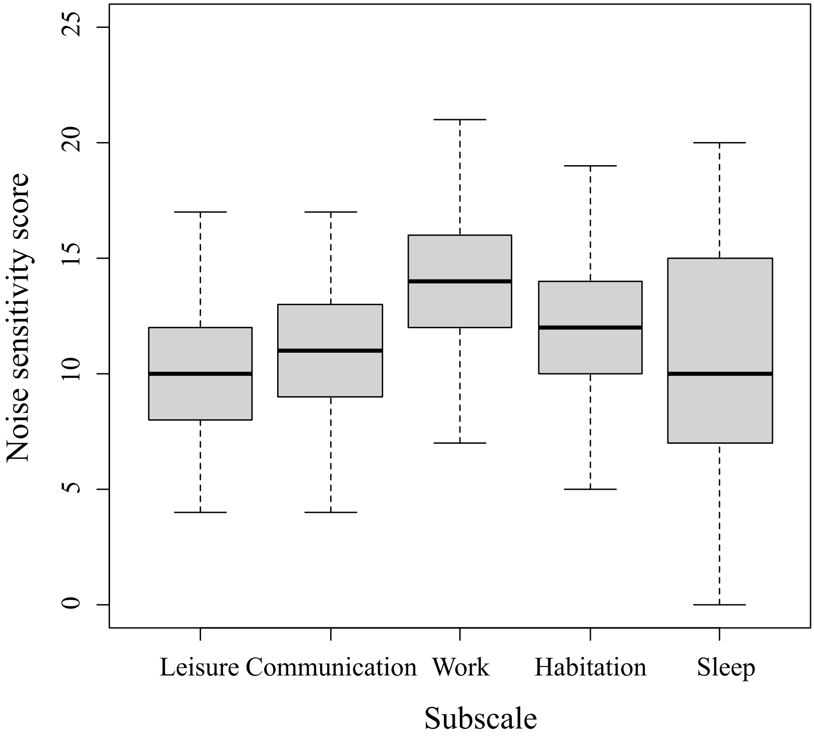
(a)

(b)

(c)

(d)

Figure 5


Noise sensitivity score
0
5
10
15
20
25
Leisure
Communication
Work
Habitation
Sleep
Subscale