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Correlations between standardised and real impact sound sources in lightweight wooden structures

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ABSTRACT

This study aimed to understand the correlation between standard impact sound sources and real impact sources in lightweight floor structures. Six real impact sources (adult walking, child running, child jumping on the floor, and three objects falling) were used to be compared with standard impact sources (i.e. tapping machine and impact ball). Measurements were conducted on a lightweight timber joist floor. Impact sound pressure levels (SPLs) produced by the standard impact sources were measured on the four floor structures with or without carpet tiles. For the real impact sources, two walkers wearing socks and slippers walked at different speeds (normal and fast) along three paths, while two children ran along the three paths and jumped at four positions. Also, the SPLs generated by dropped objects were measured at five positions. Seven standardised single-number quantities (SNQs) were calculated for the tapping machine and the impact ball, while three noise ratings (L_{Aeq}, L_{AFmax}, and L_N) were also computed from the sound recordings of the real impact sources. Both the tapping machine and the impact ball showed similar frequency characteristics with the real impact sources across all the floor structures. All the SNQs for the tapping machine and the impact ball were highly correlated with the energy-based noise ratings of the adult walking and little differences were found across walking speeds and footwear. Similar tendencies were observed from other real impact sources, indicating the high correlations between the standardised SNQs of the tapping machine and the impact ball and the noise ratings.

1. Introduction

The impact sound insulation of floors has been evaluated using single-number quantities (SNQs), which are determined from measurements with standard impact sources such as the tapping machine and the impact ball. These SNQs aim to indicate impact sound insulation performances by linking the physical measurements with the occupants' subjective responses to impact sounds (i.e. annoyance). Thus, several studies have tried to develop SNQs via objective measurements and subjective evaluations. For lightweight impact sounds, the SNQs were calculated by comparing the measurement results with the reference curve [1], but later studies [2–4] have suggested different reference curves and SNQs for rating impact sound insulation based on the measurements and questionnaire surveys. Auditory experiments were also conducted in controlled conditions to develop the SNQs of impact sounds. Several studies [5,6] have focused on heavyweight structures (e.g., concrete slabs) and heavyweight impact sources, such as impact ball. In particular, a recent study [6] reviewed many SNQs for heavyweight impact sounds using both standard and real impact sounds; however, lightweight impact sources were not considered. A similar approach [7,8] was used to develop the SNQs for lightweight impact sounds. Kylliäinen, et al. [9] recently conducted a psychoacoustic experiment using real impact sounds recorded from heavyweight structures and investigated the relationships between SNQs and subjective responses.

Different attempts have also been made to understand SNQs by calculating the relationships between the SNQs and the noise ratings. Blazier Jr and DuPree [10] and Rabold et al. [11] recorded the impact sounds produced by a tapping machine and a person walking in wooden buildings and analysed their characteristics using Zwicker's loudness levels and impact sound levels. Warnock [12] calculated the correlation coefficients between the SNQs of a tapping machine and the simple ratings of walking sounds such as A-weighted sound pressure level (SPL). Jeon, et al. [13] introduced additional real impact sources such as an adult walking, a child running, and a bottle being dropped on a concrete slab with three standard impact sources (tapping machine, impact ball, and

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bang machine). They calculated the correlation coefficients among the spectral characteristics of each real and standard impact source; however, other noise ratings were not considered. Moreover, Yeon, et al. [14] investigated the relationships between the simple noise ratings (i.e. $L_{A,Fmax}$, $L_{Amin,}$ and L_{Aeq}) and the SNQs for standard and real impact sources. Furthermore, Kylliäinen, et al. [15] extensively reviewed the correlations between the SNQs and the various noise ratings of walking on concrete floors. A total of eight SNQs regarding lightweight impact sounds were introduced with three simple noise ratings ($L_{A,Fmax}$, $L_{Aeq,}$ and L_N). However, previous studies on the correlations between SNQs and noise ratings had several limitations. First, most of the studies only investigated the SNQs of lightweight or heavyweight impact sounds, thus introducing the tapping machine as a standard lightweight impact source or the bang machine and the impact ball as standard heavyweight impact sources. Second, the majority of studies focused on adults walking, and other real impact sources were not considered. However, Park, et al. [16] confirmed some structure-borne impact sources in real apartment buildings such as furniture being moved, a child running, an adult walking, and small items being dropped. Third, the floor structures were not widely varied, so sound stimuli recorded from limited configurations were analysed.

This study, therefore, aims to fulfil an existing need given by a lack of research on the relationships between SNQs and noise ratings. Floor impact sounds induced by standard and real sources were recorded in a laboratory equipped with four lightweight floor structures. Two standard impact sources (tapping machine and impact ball) were used to represent lightweight and heavyweight impact sounds, respectively. Real impact sources included an adult walking, a child running and jumping, and objects being dropped. From the measurements, the standardised SNQs and the noise ratings were calculated and the correlation coefficients between them were then investigated.

2. Methods

2.1. Laboratory

The impact sound measurements and recordings were carried out in a laboratory at the Rosenheim Technical University of Applied Science in Germany. The laboratory consists of vertically adjacent source and receiving rooms which are separated by a lightweight timber joist floor. As shown in Fig. 1, the floor area of the receiving room is 14 m^2 and its volume is 53 m^3. Five 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, corresponding to that of furnished dwellings. The A-weighted level of the steady background noise level of the receiving room was lower than < 25 dB.

2.2. Tested floor structures

The measurements were carried out with the basic structure and with three commonly used lightweight floor structures as plotted in Fig. 2. The basic structure, L1, is a 22 mm thick chipboard panel supported by timber joists (220 mm height and 80 mm width) with a spacing of 625 mm on centres. Floor structure L2 was made by adding a floating floor system to L1. The floating floor system was composed of 30 mm thick honeycomb cardboard filled with gravel (54 kg/m^2) for increasing surface mass and covered by dry screed gypsum fibre boards with an additional 30 mm of thick mineral wool underneath. Floor structure L3 was formed by adding a suspended ceiling to L1, where the suspended ceiling was composed of double gypsum boards (18 mm thick each), with 100 mm thick mineral wool between the beams. Floor structure L4 was a combination of L2 and L3 with both the floating floor and the suspended ceiling on the L1. Carpet tiles were added to each floor structure as floor covering, and measurements were conducted twice with and without floor covering (i.e. Lx-a, bare structure, and Lx-b, structure with floor covering). The carpet tile used in this study is made of ribbed nylon attached to rubber with a total thickness of 5 mm and the size of each tile was 50 cm × 50 cm which is typically used in offices. A soft sealant was placed along all the edges of the floor structures with floating floors and suspended ceilings.

The basic structure, L1, is not a relevant structure for buildings due to its low impact sound insulation; however, it is included as a reference to show a wide range of floor structures in terms of sound insulation performance. Floor structure L2 is a commonly used timber joist floor for single-family houses. The floating floor is useful to reduce impact sound mostly above its mass-spring-mass resonance frequency and it also reduces flanking sound

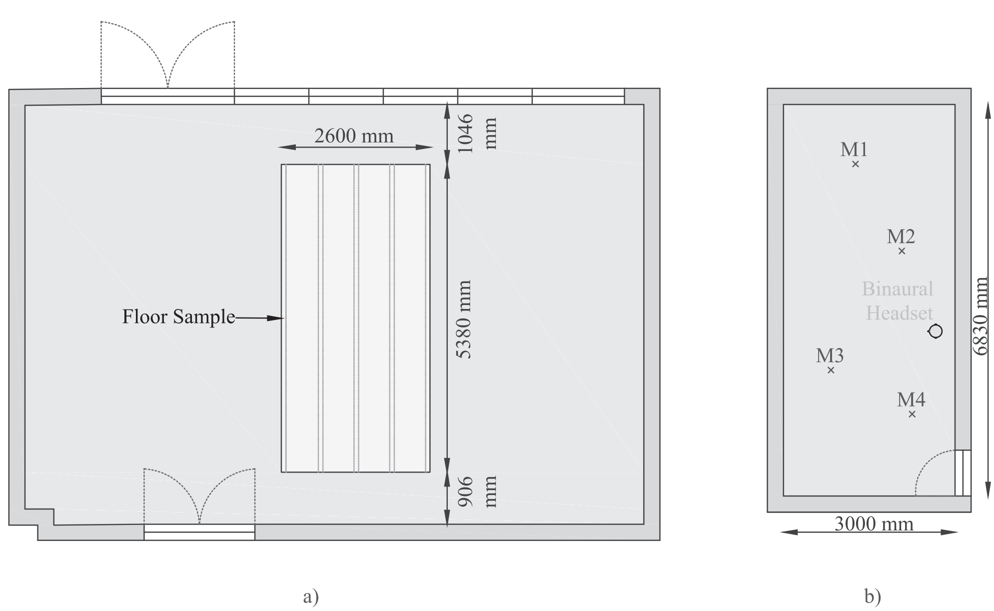

Fig. 1. A floor sample in the source room (a) and the receiving room (b) of the laboratory and its dimensions.

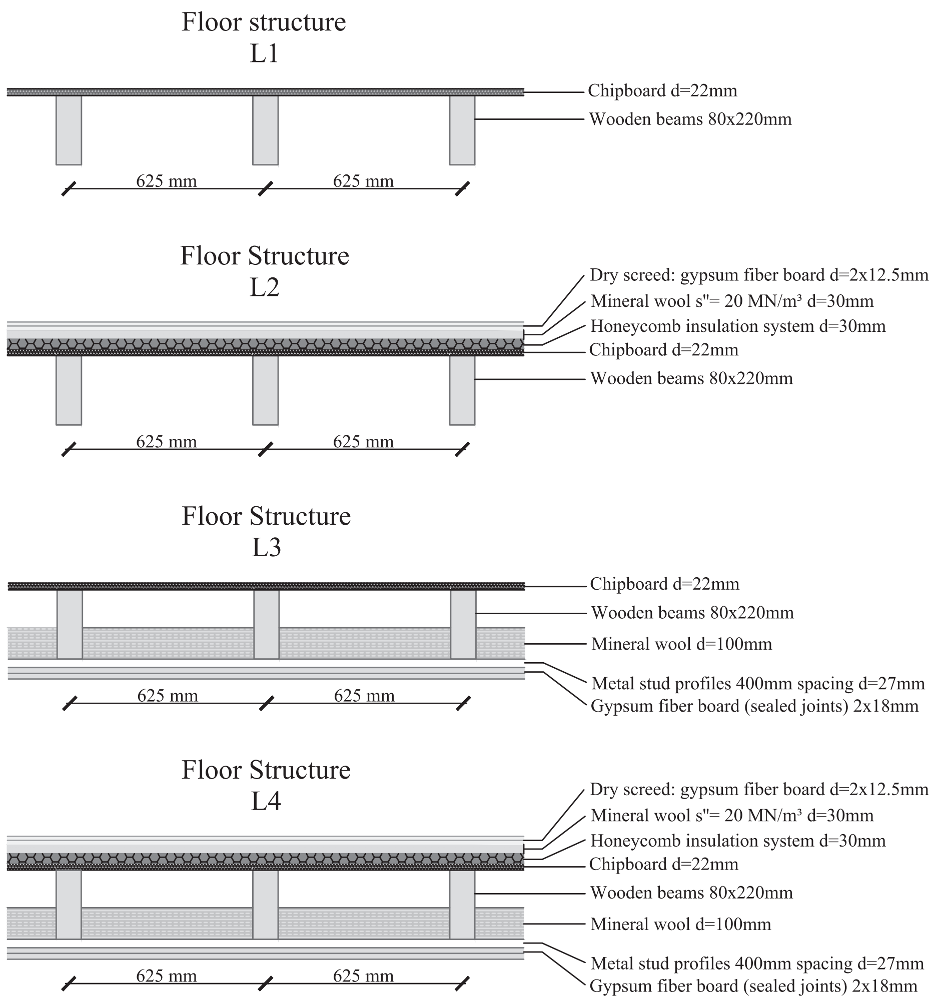

Fig. 2. Sectional details of the floor structures.

transmission. From the measurements of transmission functions, the mass-spring-mass resonance frequency of the floating floor was determined to be at approximately 48 Hz. Floor structure L3 is an alternative to structure L2 but ceiling is much lower than that of the floating floor (e.g., L2). For the considered floor construction L3, the mass-spring-mass resonance frequency of the suspended ceiling was determined as above to be approximately 26 Hz. Floor structure L4 is a typical floor construction in European countries to achieve good value for impact sound insulation in residential buildings.

2.3. Impact sound sources

The measurements were carried out using a total of eight different impact sound sources: two standardised sources and six commonly heard real impact sources. The standardised impact sources were a tapping machine (Type Nor277, Norsonic) and an impact ball (Type Nor279, Norsonic). As shown in Fig. 3(a), five impact positions for the standardised impact sources were randomly placed by covering whole floor areas with different dynamic characteristics. For example, P3 corresponds to an over-joist position, while P2 corresponds to a centralised position between adjacent joists. The tapping machine was always placed with an inclination of about 45° with respect to the joist's directions. The impact ball was dropped from a height of 1 m at the same positions, and the measurements were repeated three times in each position.

The real impact sources consisted of three footsteps and three objects falling. The three footsteps were adults walking, a child running, and a child jumping on the floor. The other three sounds were produced by objects being dropped: a 0.5 l water bottle from a height of 1 m, a 5 kg sand bag from a height of 0.5 m, and a box of wooden blocks resembling a toy (approximately 1 kg) from a height of 1 m. Fig. 3(b) illustrates the walkers' paths and the children's jumping positions. The footsteps of the adults walking were averaged for two walkers in each structure: Walker 1 (165 cm and 50 kg) and Walker 2 (172 cm and 76 kg). Several factors affecting the footsteps of the adults walking were introduced: (1) footwear, (2) walking path, and (3) walking speed. First, socks and slippers were chosen as the most commonly used footwear at home. Second, as shown in Fig. 3(b), the footsteps were performed along three different paths with similar lengths but different geometry. Furthermore, two walking speeds ('normal' at 1.8 Hz and 'fast' at 2.2 Hz [17,18]) were controlled using a metronome. The children running and jumping were recorded on three of four structures (L1, L3, and L4) because of the availability of the children. The set-up was also limited to invite the same child for the whole structures, so two children took part in separate measurements. A child (112 and 22 kg) ran and jumped on L1 and L3, while measurements on L4 were conducted with another child (105 cm and 17 kg). During the recordings, the children ran along Paths 1, 2 and 3 and jumped from a height of 20 cm above the floors on four positions, J1 to J4, as shown in Fig. 3(b). The children were wearing socks for running and jumping for their health and safety. The posi-

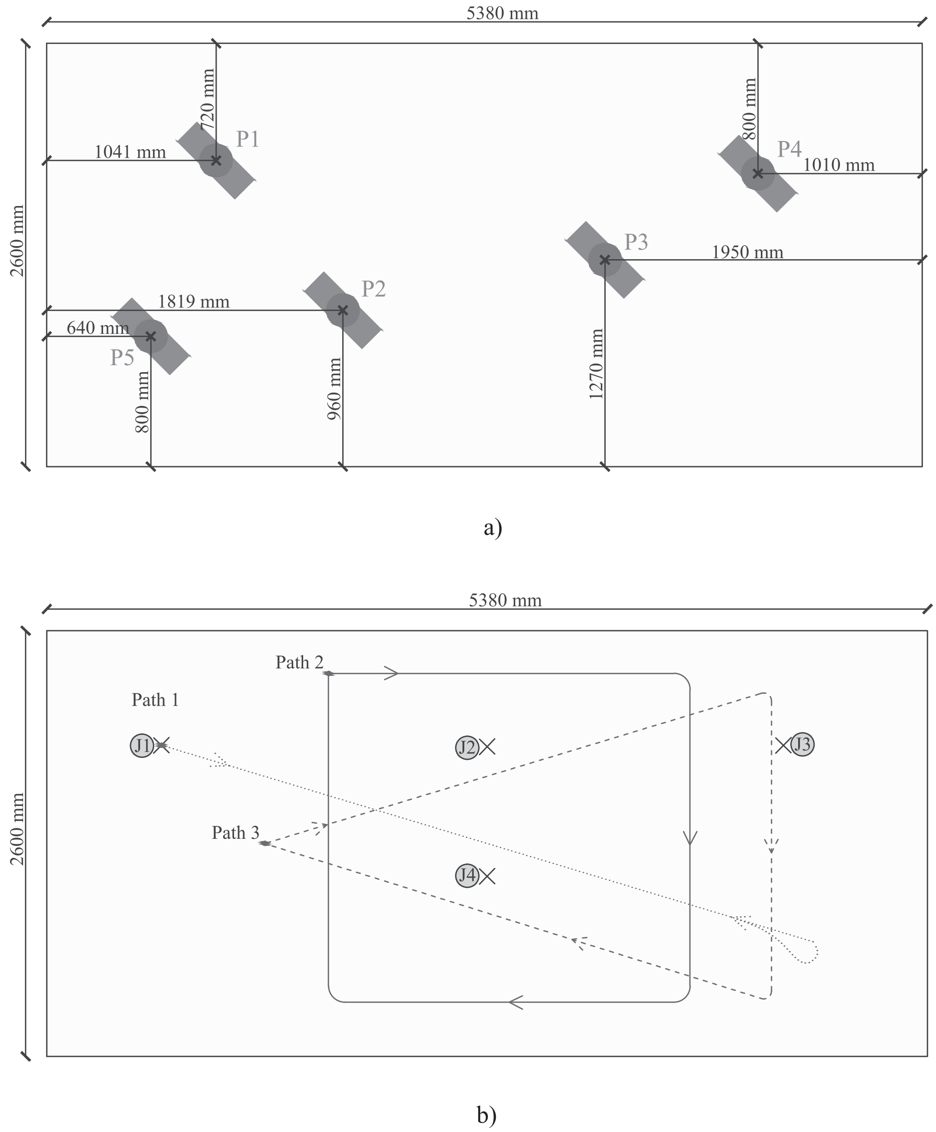

Fig. 3. Excitation positions of the impact ball and the tapping machine, P1 to P5 (a), and three paths for adults walking/children running as well as four positions for children jumping, J1 to J4 (b). The objects were dropped on five positions along Path 1, starting from J1 and approximately 1 m from one another.

tions selected for recording the objects falling were five, equally spaced along the diagonal Path 1. All the walking, jumping, and dropping of objects were repeated twice for each path and at each position. The children involved in this study were 10 and 12 years old and their mothers monitored them throughout the recordings. Before the recordings, the children were instructed to run and jump on the floor until they became familiar with the setting and were told that it would take approximately one hour for each child to complete all the recordings.

2.4. Sound recording

Two half-inch microphones (Type 378B02, PCB) connected to a sound analyser (Type Nor150, Norsonic) were placed in the receiving room. Additional recordings were performed using a binaural head equipped with half-inch microphones (Type 40HL, GRAS) [19] located in the receiving room resembling a person sitting on a sofa. The recording system was calibrated before and after the recordings using a sound calibrator (Type 4231, B&K). For the standard impact sources, four fixed microphone positions were used; thus, a total of 20 (five impact source locations *x* four microphone positions) and 60 (five impact source locations *x* three times repetition *x* four microphone positions) measurement were obtained for the tapping machine and the impact ball, respectively. The recording of the real impact sound sources was performed with two half-inch microphones fixed at positions M1 and M4 and the binaural headset.

2.5. Single-number quantities for standard impact sources

From the measurements of the standardised impact sound sources, a series of single-number quantities (SNQs), as listed in Table 1, were calculated. For the tapping machine, the normalised impact SPLs, $L_{n,}$ were calculated from the spatial averages of 20 impact SPL measurements with the reverberation time and background noise levels through the sound analyser. The standardised SNQs were then determined based on the normalised impact SPLs L_n according to ISO 717–2 [1]: the weighted normalised impact SPLs, $L_{n,w}$, the sum of $L_{n,w}$ and the spectrum adaptation terms C_I and $C_{I50\text{-}2500}$. In addition, the inverse A-weighted impact SPL, $L_{n,Aw}$ was also calculated according to JIS A 1419-2 [20]. For the heavy-weight impact source (i.e. impact ball), three SNQs in JIS A

Table 1
Standardised single-number quantities (SNQs) for lightweight and heavyweight impact sources and corresponding standards.

Tapping machine		Impact ball	
SNQs	Standards	SNQs	Standards
$L_{n,w}$	ISO 717–2	$L_{i,Fmax,AW}$	JIS A 1419–2, KS F 2863–2
$L_{n,w} + C_I$	ISO 717–2	$L_{i,Fmax,r}$	JIS A 1419–2, KS F 2863–2
$L_{n,w} + C_{I(50\text{-}2500)}$	ISO 717–2	$L_{i,avg,Fmax,(63\text{-}500Hz)}$	KS F 2863–2
$L_{n,Aw}$	JIS A 1419–2, KS F 2863–1		

1419-2 [20] and KS F 2863-2 [21] were calculated: the inverse A-weighted impact SPL, $L_{i,Fmax,Aw}$, the A-weighted impact SPL, $L_{i,Fmax,r}$, and the arithmetic average of maximum SPLs in octave bands from 63 Hz to 500 Hz, $L_{i,avg,Fmax\ (63\text{-}500Hz)}$.

2.6. Noise ratings of real impact sources

Three noise ratings were chosen to characterise the recording of real impact sources according to previous studies [10,14,15]. First, the A-weighted equivalent SPL (L_{Aeq}) was calculated over the eight-second measurement period. This eight-second period corresponds to the time for the walker to complete each path at normal speed. For the dropping of an object, the recordings were edited to have four repetitions of the single impact noise with a length of two seconds each. In addition, the A-weighted maximum SPL (L_{AFmax}) and the loudness level (L_N) were calculated. The noise ratings were computed using the BK Connect data processing and signal analysis software (Type 8403, B&K). The loudness level calculation was based on Zwicker's loudness model of time-varying sounds according to ISO 532–1 [22]. The calculation of noise ratings from the footsteps was carried out separately for the two walkers. Each figure was calculated as an arithmetic average of twelve recordings: (1) averaging three different walking paths repeated twice wearing slippers and socks and (2) averaging three different paths repeated twice at normal and fast walking speeds. The footsteps sounds generated by the children were not consistent; thus, the noise ratings for the children running and jumping were calculated for one selected sound recording per each (path 1 for running and J4 for jumping, see Fig. 3(b)). For the dropping of the sand bag and the wooden blocks, the noise ratings were averaged over ten recordings (five positions measured twice). The water bottle dropping sounds were also varied across the second bounce and the subsequential rolling of the bottle, especially without the carpet; thus, just one signal with the highest L_{Aeq} was chosen for the calculations.

3. Results and discussion

3.1. Impact sound pressure levels of standard and real impact sources

The normalised impact SPLs generated by the tapping machine and the maximum impact SPLs (L_{Fmax}) of the impact ball across the eight configurations are plotted in Fig. 4. For the tapping machine sounds (Fig. 4(a)), the SPLs were dominant at high frequencies for the basic structure (L1) but the SPLs at high frequencies were much reduced for other structures (L2–L4). On the contrary, the impact ball sounds (Fig. 4(b)) showed dominant sound energies at low frequencies for all the structures. The SPLs were clearly reduced by adding the floating floor and the suspended ceiling (structure L4) to L1, indicating significant increases of insertion losses. In general, for the tapping machine, the SPLs at high frequencies were more reduced than those at low frequencies, confirming the findings of previous studies [10,23,24]. For instance, the SPL at 1 kHz was reduced by around 60 dB, whereas the maximum reduction of SPLs at 50 Hz was around 10 dB. Similarly, the noise reductions of the impact ball sounds were relatively high at high frequencies. The effectiveness of the floating floor (L2) and the suspended ceiling (L3) varied across the frequency range. At 50 Hz, the floating floor was almost 10 dB more effective in reducing the SPLs for both standardised sources compared to the suspended ceiling. This might be due to the higher impedance mismatch of the source and the first contact layer in the case of the floating floor. Above 50 Hz, for the tapping machine, the floor structures L2 and L3 showed similar tendencies across the frequency ranges. However, above 50 Hz, the impact ball sounds for L3 were lower compared to those for L2. The structure with both a floating floor and a suspended ceiling installed (L4) showed the greatest decreases of the SPLs for both the tapping machine and the impact ball. More specifically, the SPL reductions significantly increased with increasing frequency for the tapping machine and the impact ball. The noise reductions with L4 in this study were greater than those with the concrete structure with a floating floor and a suspended ceiling [23] because the flanking paths in situ led to less noise reduction in a previous study [23]. The effects of the carpet on the SPLs were different across the standardised sources. For tapping machine sounds, adding carpet tiles to the structures helped to reduce the SPLs at high frequencies above 500 Hz. For the impact ball sounds in contrast, the SPL reductions by adding carpet tiles were minimal except for the basic structure (L1). This finding is consistent with those of the previous studies [12,25,26], in which a carpet is not useful to mitigate heavyweight impact sounds.

Fig. 5 illustrates the impact SPLs of the real sources as a function of L_{Fmax}. The impact SPLs of human footsteps were averaged across the paths, walking speeds, and walkers. The separated results can be found in the Supplementary data (Fig. S1). Overall, the impact SPLs at low frequencies were dominant for most sources except for the droppings of the water bottle and the wooden blocks on the reference structure (L1). Among the footstep sounds, the child running (Fig. 5(b)) and jumping (Fig. 5(c)) presented around a 10 dB higher SPL than the adult walking (Fig. 5(a)). For example, the averaged SPLs below 100 Hz varied from 60 dB to 74 dB for the adult walking, while the child running and jumping showed a range between 64 dB and 79 dB. The SPLs of the adult walking at 50 Hz were similar to those of the adult walking measured from 210 mm thick concrete slabs with or without a floating floor consisting of resilient isolator, lightweight concrete and finishing mortar [27,28]. In contrast, the child running or jumping generated greater SPLs than the heavyweight floor structures, which showed 55–70 dB for the 210 mm thick concrete bare slab and 45–60 dB for the 210 mm thick concrete slab with a floating floor. This implies that the heavyweight floor structures were more effective to reduce SPLs at low frequencies compared to the lightweight structures. However, further data from both heavyweight and lightweight floors are needed for a detailed comparison. Installing the floating floor and the suspended ceiling attenuated the SPLs mostly at mid- and high frequencies rather than at low frequencies (<100 Hz).

The effects of the different sound insulation treatments were also clearly distinguishable, and similar tendencies were observed. The basic structure (L1) showed the highest SPLs, whereas L4, with both a floating floor and a suspended ceiling, offered the best sound insulation performance. The structures with either a floating floor or a suspended ceiling showed SPLs between those of L1 and L4; at low frequencies below 100 Hz, the structure with the suspended ceiling (L3) performed better than that with the floating floor (L2), while L2 was more effective than L3 above 100 Hz. Overall, for this specific construction the use of a dry screed in a light-

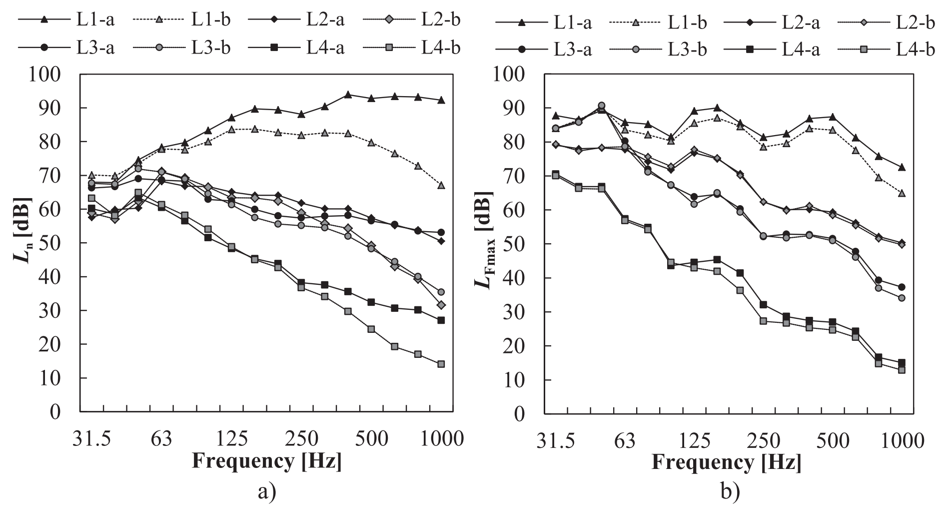

Fig. 4. Frequency characteristics of floor impact sounds generated by the tapping machine and the impact ball across four floor configurations with carpet tiles (grey) and without carpet tiles (black). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

weight structure has a minor impact compared to heavyweight concrete floors because of the big bare floor difference of mass per unit area. The improvement of sound insulation by adding carpet tiles was visible mostly at high frequencies and varied depending on the source and the floor structure. In particular, the carpet tiles were more effective for the impact sources with dominant impact force at high frequencies. Among the real impact sources, the three dropped objects in this study (wooden blocks, water bottle and sand bag) were expected to have stronger impact force at high frequencies than three footsteps with dominant impact force at low frequencies below 31.5 Hz [29]. In the basic structure (L1), three object fallings showed greater decreases in SPL at high frequencies above 500 Hz with carpet tiles compared to the footsteps except for child running which was biased due to low repeatability. For the object fallings, the effectiveness of the carpet tiles at high frequencies was still significant in the structures with floating floors or suspended ceilings. However, the SPL attenuations from the carpet in other structures were lower than those in L1 because the floating floor and suspended ceiling also reduced SPLs at high frequencies. For adults walking, children running, and sand bag being dropped, the carpet led to significant SPL decreases in the basic structure (L1). Specifically, for child running, a large decrease of sound pressure level (>10 dB) was found at high frequencies in L1 in the presence of carpet tiles. This decrease is greater than other studies using tapping machine in lightweight floors. This is because the real impact sources such as child running showed large variations in impact force and sound pressure level due to low repeatability. In addition, for the droppings of the water bottle and the wooden blocks, the SPL attenuations from the carpet were significant from the structures with floating floors or suspended ceilings as well as L1.

Differences in frequency characteristics were observed in Figs. 4 and 5 across the sources. The variations are explained by the differences in mechanical impedance and impact force of the sources. Because the actual exciting force acting on a floor structure depends on the ratio of the mechanical impedances of the source and the floor. Several previous studies have reported the mechanical impedance and impact force of both standard and real impact sources [29–31]. In particular, Jeon, et al. [29] reported that the first resonance frequencies of the impact ball and human barefoot were about 20 Hz and 4 Hz, respectively. The hammer of tapping machine does not have a resonance frequency and the mechanical impedance of the hammer increase as the frequency increased. In Fig. 4(b), the structure with a suspended ceiling (L3) had a greater SPL at 31.5 Hz than the structure with a floating floor (L2). This might be due to the impedance matching of impact ball and the floor structure with a low mass-spring-mass resonance frequency (experimentally determined to be at approximately 26 Hz, see above). In the present study, the impact ball produced greater sound pressure levels than adult walking, the child running, and child jumping. This shows a good agreement with the previous study [29] which reported that the impact ball had greater impact force than real impact sources such as adult walking and child running/jumping. In addition, the child jumping showed a slightly greater sound pressure level at 31.5 Hz than the child running in Fig. 5, confirming the previous study in which a child jumping had greater impact force at 31.5 Hz than a child running [29].

3.2. Correlations between frequency characteristics of standard and real impact sources

The correlation coefficients between the frequency characteristics in the range between 50 Hz and 1 kHz (which includes the majority of the energy for impact sources) in one-third octave bands of the standard and real impact sources were calculated across the floor structures to see whether standard impact sources represent real impact sources in different floor structures (Table 2). The correlation analyses were conducted separately for the lightweight (i.e. tapping machine) and heavyweight (i.e. impact ball) impact sounds, while the SPLs of the real impact sources were in L_{Fmax}. Most of the correlation coefficients were significant except for several cases in the basic structure (L1). The low correlation coefficients between wooden blocks and standard impact sources on L1-b are due to dissimilarity in frequency characteristics in the specific frequency ranges (50–200 Hz for impact ball and 250–500 Hz for tapping machine). Fisher r-to-z transformation [32] was used to test the significance of the difference between correlation coefficients for the tapping machine and the impact ball. The transformation showed that the difference in correlation coefficients between the real sources and the tapping machine was significantly lower than those between the real sources and the impact ball only on the basic structure without a carpet (L1-a). For the other floor structures, the difference in correlation coefficients was not significant except for the adult walking on structure L4-a, for which the correlation coefficient of the tapping machine is significantly greater than that of the impact ball (see Supplement Table S1). This is mainly because the sound energy

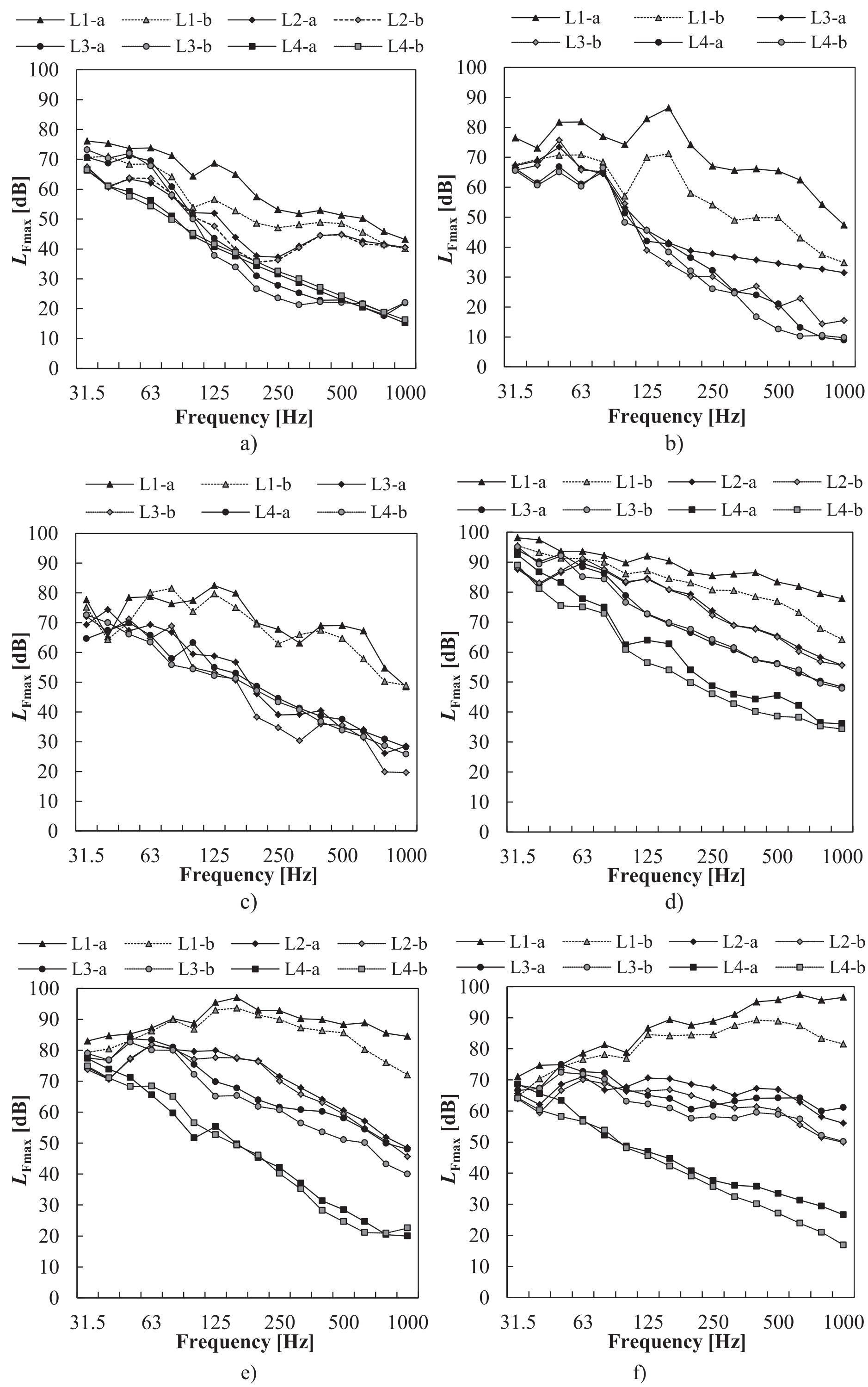

Fig. 5. Frequency characteristics of floor impact sounds generated by real impact sources across the floor configurations with carpet tiles (grey) and without carpet tiles (black): (a) adults walking, (b) child running, (c) child jumping, (d) sand bag being dropped, (e) water bottle being dropped, and (f) wooden blocks being dropped. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

at high frequencies was significantly reduced by the carpet, the floating floor, and the suspended ceiling; thus, the low frequency components were dominant for the tapping machine sounds. This result is not consistent with those of previous studies [13,33,34], in which the frequency characteristics of the impact ball sound were more similar to real impact sounds. However, those studies did not test the statistical significance of the differences in correlation coefficients, and the differences between the impact ball and the tapping machine were insignificant. For instance, for several real impact sources such as jumping from a chair, the difference in correlation coefficients between the impact ball and the tapping machine was just 0.01 in a previous study [13].

Table 2
Correlations coefficients obtained confronting one-third frequency bands between 50 Hz and 1 kHz in each floor configuration of real impact sound sources in term of L_{Fmax} with standard impact sources, L_n for the tapping machine and L_{Fmax} for the impact ball (* $p < 0.05$ and ** $p < 0.01$).

		Adult walking	Child running	Child jumping	Sand bag	Water bottle	Wooden blocks
Tapping machine (L_n)	L1-a	−0.857**	−0.619*	−0.592*	−0.764**	0.07	0.955**
	L1-b	0.29	0.607*	0.726**	0.668**	0.929**	0.42
	L2-a	0.530*			0.924**	0.961**	0.917**
	L2-b	0.524*			0.948**	0.981**	0.990**
	L3-a	0.954**	0.965**	0.969**	0.983**	0.988**	0.926**
	L3-b	0.835**	0.908**	0.947**	0.967**	0.983**	0.956**
	L4-a	0.998**	0.987**	0.984**	0.986**	0.984**	0.994**
	L4-b	0.977**	0.974**	0.994**	0.962**	0.976**	0.997**
Impact ball (L_{Fmax})	L1-a	0.738**	0.906**	0.905**	0.839**	0.658**	−0.49
	L1-b	0.709**	0.865**	0.859**	0.892**	0.846**	−0.11
	L2-a	0.713**			0.984**	0.964**	0.883**
	L2-b	0.635*			0.986**	0.972**	0.956**
	L3-a	0.932**	0.944**	0.956**	0.975**	0.976**	0.884**
	L3-b	0.899**	0.942**	0.964**	0.978**	0.972**	0.959**
	L4-a	0.985**	0.977**	0.971**	0.989**	0.984**	0.988**
	L4-b	0.975**	0.970**	0.982**	0.976**	0.959**	0.985**

3.3. Single-number quantities and noise ratings

The standardised SNQs for the lightweight and heavyweight impact sounds are listed in Table 3. The weighted normalised impact SPL ($L_{n,w}$) and the spectrum adaptation terms were calculated using the sound analyser according to ISO 717–2 [1], while Excel spreadsheets were used for other SNQs. The lightweight and heavyweight impact sounds were significantly reduced in terms of the SNQs. In particular, the decreases of the SNQs for the lightweight impact sounds were greater than those for the SNQs associated with the heavyweight impact sounds. For example, $L_{n,w}$ was reduced by around 35 dB by adding a floating floor or a suspended ceiling to the basic structure (L1) and was further decreased by approximately 20 dB with both treatments (L4). Instead, $L_{i,Fmax,r}$ was reduced by around 24 dB with either a floating floor or a suspended ceiling and was decreased for L4 by an additional 10 dB. Several SNQs such as $L_{n,w}$, $L_{n,w}$ + $C_{I(50-2500)}$, and $L_{i,Fmax,r}$ did not vary across the floor structures with either a floating floor or a suspended ceiling. For most floor structures except for L1-a and L3-a, the SNQs were penalised by the spectrum adaptation terms C_I and $C_{I(50-2500)}$; the application of C_I increased the ratings by <5 dB, and $C_{I(50-2500)}$ increased the ratings by up to 15 dB (for L4). Among the SNQs related to the tapping machine, $L_{n,Aw}$ showed the greatest values, rating L1-a and L3-a around 6 dB greater and L1-b, L2, L3-b, and L4 around 10 dB more strictly than $L_{n,w}$. For the SNQs of the impact ball, $L_{i,Fmax,AW}$ and $L_{i,avg,Fmax,(63-500Hz)}$ showed the minimum and maximum values, respectively, for each floor structure, the differences between them varying from 8 dB to 11 dB. On the other hand, $L_{i,Fmax,r}$ and $L_{i,avg,Fmax,(63-500Hz)}$ were similar except for L1-b, L2-a, and L2-b, with small differences<2 dB. The differences in the SNQs for the structures with and without carpet tiles were minor for L2, L3, and L4, with the exception of $L_{n,w}$, which showed around a 6 dB difference between L3-band L3-a. A substantial difference between SNQs for floor structures with and without carpet tiles was found only in the basic structure (L1); the SNQs of the tapping machine sound showed a 10–16 dB difference between L1-a and L1-b, while the SNQs extracted from the heavyweight sounds demonstrated a 3–6 dB difference between L1-a and L1-b. The SNQs in Table 3 can be explained by the following considerations of the floor structure characteristics. The structure L2 with a floating floor is modelled by a mass-spring-mass system. Floating floor is useful to reduce impact sounds above mass-spring-mass resonance frequency and it has an additional advantage of adding mass to the basic structure. Consequently, L2 had lower SNQs than L1 for the tapping machine and the impact ball. Compared to L1, the SNQs for the tapping machine were more reduced than those for the impact ball. It is because mass-spring-mass resonance frequency (≈48 Hz) is within the frequency range of the SNQs for the impact ball. Similarly, $L_{n,w}$ + $C_{I(50-2500)}$ showed the smallest improvement among the SNQs for the tapping machine because the floating floor resonance frequency also affected the frequency range of the adaptation term. The structure L3 with a suspended ceiling also can be modelled by a mass-spring-mass system and it had lower mass-spring-mass resonance frequency (≈26 Hz) than the floating floor (L2) The structure L3 was more effective in reducing impact SPLs above this resonance frequency; thus, the standardised SNQs in L3 were lower than those in L2. $L_{n,w}$ + $C_{I(50-2500)}$ also had less improvement because the adaptation term frequency range is affected by the resonance frequency as well. The structure L4 with a floating floor and suspended ceiling had double mass-spring-mass systems so it had more advantage compared to L2 and L3. It showed the smallest SNQs for both the tapping machine and the impact ball. The structure L4 had the lowest resonance frequency (≈22 Hz) which still affects the calculations of the SNQs for the impact ball and the adaptation term, $C_{I(50-2500)}$. Soft floor coverings such as carpet tiles alter force inputs and they improve the impact sound insulation above a cut-off frequency which is

Table 3
Standardised SNQs of different floor configurations for the tapping machine and the impact ball.

		L1-a	L1-b	L2-a	L2-b	L3-a	L3-b	L4-a	L4-b
Tapping machine	$L_{n,w}$	92.6	76.5	56.7	54.3	57.1	50.7	37.0	37.4
	$L_{n,w} + C_I$	87.6	76.5	57.7	56.3	54.1	52.7	40.0	41.4
	$L_{n,w} + C_{I(50-2500)}$	87.4	77.0	59.7	60.0	60.0	61.7	51.0	52.0
	$L_{n,Aw}$	97.8	85.6	66.6	64.9	63.7	61.8	48.7	50
Impact ball	$L_{i,Fmax,AW}$	81	77	61	61	57	56	47	46
	$L_{i,Fmax,r}$	88	82	65	65	64	64	54	54
	$L_{i,avg,Fmax,(63-500Hz)}$	89	86	71	72	66	66	55	54

determined by the contact stiffness. In particular, the impact sound improvement is found at high frequencies. Thus, the SNQs for the tapping machine showed greater reductions than those for the impact ball across all the structures.

The noise ratings of lightweight and heavyweight real impact sounds are listed in Table 4. For Walker 1, the differences between speeds (i.e. normal and fast) were <3 dB for L_{Aeq} and L_{AFmax} and <0.5 phon for L_N. On the other hand, Walker 2 showed greater differences: 5 dB for L_{Aeq}, 7 dB for L_{AFmax}, and 2 phon for L_N. The differences in SPLs between walkers are due to differences in weight and walking patterns [35]. Changing footwear from socks to slippers caused major within-walker difference for Walker 1: 5 dB for L_{Aeq}, 6 dB for L_{AFmax}, and 1 phon for L_N. These results are consistent with those of a previous study [15], which reported decreased noise ratings with soft-heeled shoes in heavyweight structures with different floor coverings. However, Walker 2 showed less differences between footwear and slippers than Walker 1. Also, the sound insulation performances of the floor structures were slightly different between the walkers because impact sound levels are affected by body weight and walking style. In particular, contrary to the heavyweight floor such as the concrete slab, the walkers strongly perceived the floor vibration caused by their walking on the lightweight structure which might change their walking styles. Lee, et al. [36] also reported that the perception of floor vibration induced by humans walking varied even in the heavyweight floor structures with resilient isolators. The noise ratings of a child

Table 4
Noise ratings (L_{Aeq}, L_{AFmax} and L_N) of different floor configurations for real impact sources: (a) adults walking and (b) child running and jumping and dropped objects. (a).

		Walker 1 (165 cm, 50 kg)				Walker 2 (176 cm, 72 kg)			
		Normal	Fast	Slipper	Socks	Normal	Fast	Slipper	Socks
L1-a	L_{Aeq}	49.3	51.2	47.7	52.8	43.0	44.4	44.2	43.2
	L_{AFmax}	57.7	60.6	56.4	61.9	51.6	53.5	53.0	52.0
	L_N	36.7	36.9	36.6	37.1	35.8	36.1	35.9	35.9
L1-b	L_{Aeq}	44.8	45.8	44.7	45.8	40.3	42.5	42.1	40.6
	L_{AFmax}	53.8	53.9	53.4	54.3	48.6	51.4	50.8	49.3
	L_N	36.1	36.3	36.1	36.3	35.3	35.7	35.6	35.4
L2-a	L_{Aeq}	38.3	39.5	37.6	40.3	37.4	39.8	38.7	38.5
	L_{AFmax}	48.0	49.1	47.8	49.3	45.7	49.1	47.6	47.2
	L_N	35.1	35.4	35.0	35.5	34.9	35.3	35.0	35.1
L2-b	L_{Aeq}	37.8	39.3	37.7	39.4	34.6	37.6	36.7	35.5
	L_{AFmax}	47.2	48.3	46.9	48.6	46.1	48.5	48.6	46.0
	L_N	35.0	35.3	35.0	35.3	33.9	34.7	34.5	34.2
L3-a	L_{Aeq}	37.9	38.7	36.2	40.4	37.6	38.2	35.6	38.0
	L_{AFmax}	47.4	48.0	45.5	49.9	46.6	46.5	44.7	48.2
	L_N	33.7	33.8	33.3	34.2	29.3	30.1	28.9	30.4
L3-b	L_{Aeq}	38.9	39.2	36.7	41.4	38.6	36.2	37.9	36.9
	L_{AFmax}	47.6	48.3	46.0	49.9	47.9	44.5	44.7	47.8
	L_N	33.9	33.9	33.4	34.7	31.5	29.4	30.1	30.8
L4-a	L_{Aeq}	31.0	32.2	31.7	31.5	32.9	37.8	34.7	35.9
	L_{AFmax}	39.8	41.3	41.1	40.0	42.2	48.0	45.4	44.8
	L_N	29.6	29.9	29.8	29.7	28.4	30.0	29.1	29.3
L4-b	L_{Aeq}	31.1	33.0	32.9	31.1	34.6	30.2	33.1	31.5
	L_{AFmax}	39.8	41.6	41.8	39.6	38.2	45.5	41.5	42.2
	L_N	29.6	30.2	30.2	29.6	27.4	29.1	28.0	28.5

		Child running	Child jumping	Sand bag	Water bottle	Wooden blocks
L1-a	L_{Aeq}	60.8	63.3	76.9	85.0	98.2
	L_{AFmax}	73.6	73.2	86.2	94.3	102.2
	L_N	37.8	38.1	39.4	40.1	41.0
L1-b	L_{Aeq}	47.9	60.3	69.4	80.2	85.8
	L_{AFmax}	59.6	70.0	78.9	90.5	92.8
	L_N	36.4	37.8	38.7	39.6	40.1
L2-a	L_{Aeq}			65.9	64.3	64.0
	L_{AFmax}			75.9	73.1	70.8
	L_N			38.4	37.9	38.0
L2-b	L_{Aeq}			63.6	63.3	58.1
	L_{AFmax}			73.7	71.6	64.9
	L_N			38.2	37.5	37.4
L3-a	L_{Aeq}	37.1	41.2	58.4	58.0	66.4
	L_{AFmax}	46.0	50.7	68.6	66.3	70.2
	L_N	33.7	35.0	37.6	37.6	38.6
L3-b	L_{Aeq}	35.8	39.8	58.3	54.3	57.0
	L_{AFmax}	47.9	49.3	68.6	62.8	63.5
	L_N	32.8	34.4	37.7	37.0	37.6
L4-a	L_{Aeq}	34.2	39.2	49.2	42.4	40.0
	L_{AFmax}	43.8	49.5	58.6	51.5	46.8
	L_N	30.1	31.4	36.1	34.8	34.8
L4-b	L_{Aeq}	33.5	36.9	50.0	43.2	36.9
	L_{AFmax}	44.6	46.6	59.9	51.1	43.0
	L_N	29.9	31.0	34.4	34.6	34.0

jumping were greater than those of a child running across the floor structure because a child jumping has greater impact force than a child running [29]. Among the dropping of objects, the wooden blocks caused the highest values on L1, but the differences between the sources were insignificant for other structures (L2–L4). Standard deviations of noise ratings for the adults walking with different footwear and paces were also calculated to examine the variations. For most noise ratings, the standard deviations of L_{Aeq} were lower than 3 dB and the maximum was 4.6 dB for the Walker 2. Similarly, the standard deviations of L_{AFmax} were below 4 dB for the most cases except for some of the Walker 2 on L2-b (5.8 dB) and L3-b (6.4 dB). Most standard deviations of L_{N} were lower than 1 dB, which were smaller standard deviations than L_{Aeq} and L_{AFmax}.

3.4. Correlation coefficients between single-number quantities and noise ratings

The correlation coefficients between SNQs and noise ratings were averaged across the floor structures (L1–L4) and mean correlation coefficients are listed in Table 5 for the tapping machine and the impact ball separately. All the correlation coefficients were statistically significant and greater than 0.7, indicating that the current standardised SNQs are satisfactory. High correlation coefficients of the tapping machine can be explained by the frequency characteristics plotted in Fig. 4. In the basic structure (L1), the SPLs produced by the tapping machine were significantly different from those generated by impact ball and real impact sources. However, the SPLs produced by the tapping machine were significantly reduced at high frequencies by adding a floating floor or suspended ceiling. Thus, the SPLs of the tapping machine in the structures L2–L4 showed similar characteristics with other sources by showing dominant SPLs at low frequencies. These correlation coefficients in Table 5 were much greater than those for the tapping machine from a concrete slab [15]. The disagreement between this study and previous studies might be mainly due to the floor structures and their sound insulation performances. Kylliäinen, et al. [15] conducted their measurements on a 265 mm thick concrete slab with nine floor coverings; thus, the impact sound levels were much lower than those of this study. For instance, L_{AFmax} for a human walking while wearing socks varied from 13.4 to 32.6 dB. In addition, the impact sound levels of a human walking were lower at the mid- and high frequencies compared to those in this study. For both the tapping machine and the impact ball, the SNQs had greater correlation coefficients with the energy-based noise ratings (L_{Aeq} and L_{AFmax}) than L_{N} for all the structures. Insignificant differences in correlation coefficients were found across walking speeds (i.e. normal and fast) and footwear (i.e. slipper and socks). Kylliäinen, et al. [15] reported that most sounds induced by walking while wearing socks were not correlated with the SNQs in the con-

Table 5
Correlation coefficients between the standardised SNQs and the noise ratings of real impact sources ($^{*}p < 0.05$ and $^{**}p < 0.01$).

			Tapping machine				Impact ball		
			$L_{\mathrm{n,w}}$	$L_{\mathrm{n,w}} + C_{\mathrm{I}}$	$L_{\mathrm{n,w}} + C_{\mathrm{I(50\text{-}2500)}}$	$L_{\mathrm{n,Aw}}$	$L_{\mathrm{i,Fmax,AW}}$	$L_{\mathrm{i,Fmax,r}}$	$L_{\mathrm{i,avg,Fmax,\ (63–500Hz)}}$
Walker 1 (165 cm, 50 kg)	Normal pace	L_{Aeq}	0.983**	0.983**	0.976**	0.985**	0.974**	0.984**	0.972**
		L_{AFmax}	0.980**	0.979**	0.961**	0.980**	0.976**	0.978**	0.977**
		L_{N}	0.867**	0.873**	0.811*	0.870**	0.899**	0.864**	0.933**
	Fast pace	L_{Aeq}	0.991**	0.992**	0.984**	0.993**	0.980**	0.989**	0.974**
		L_{AFmax}	0.988**	0.985**	0.975**	0.987**	0.969**	0.977*	0.964*
		L_{N}	0.870**	0.878**	0.813*	0.875**	0.904**	0.866**	0.937**
	Slipper	L_{Aeq}	0.986**	0.997**	0.987**	0.996**	0.991**	0.997**	0.982**
		L_{AFmax}	0.986**	0.997**	0.978**	0.995**	0.994**	0.993**	0.988**
		L_{N}	0.878**	0.890**	0.824*	0.886**	0.917**	0.878**	0.948**
	Socks	L_{Aeq}	0.971**	0.963**	0.956**	0.966**	0.948**	0.961**	0.948**
		L_{AFmax}	0.969**	0.957**	0.947**	0.961**	0.942*	0.953**	0.944**
		L_{N}	0.848**	0.851**	0.793*	0.849**	0.875**	0.843**	0.912**
Walker 2 (176 cm, 72 kg)	Normal pace	L_{Aeq}	0.918**	0.909**	0.928**	0.914**	0.874**	0.913**	0.858**
		L_{AFmax}	0.868**	0.855**	0.845**	0.858**	0.861**	0.864**	0.876**
		L_{N}	0.812*	0.845**	0.774*	0.837**	0.883**	0.829*	0.911**
	Fast pace	L_{Aeq}	0.857*	0.848**	0.813**	0.849**	0.870**	0.848**	0.864**
		L_{AFmax}	0.834*	0.846*	0.810*	0.842*	0.853**	0.828*	0.829*
		L_{N}	0.769*	0.801*	0.711*	0.791*	0.842**	0.773*	0.857**
	Slipper	L_{Aeq}	0.949**	0.965**	0.956*	0.963**	0.965**	0.966**	0.957**
		L_{AFmax}	0.893**	0.910**	0.872**	0.905**	0.932**	0.902**	0.933**
		L_{N}	0.781*	0.818*	0.737*	0.808*	0.860**	0.796*	0.882**
	Socks	L_{Aeq}	0.913**	0.895**	0.882*	0.899**	0.892**	0.897*	0.880**
		L_{AFmax}	0.920**	0.896**	0.895**	0.902**	0.885**	0.902**	0.882**
		L_{N}	0.826*	0.853**	0.771*	0.845**	0.891**	0.831*	0.914**
Child	Running	L_{Aeq}	0.961**	0.962**	0.969**	0.963**	0.938**	0.948**	0.920**
		L_{AFmax}	0.952**	0.960**	0.972**	0.960**	0.934**	0.947**	0.917**
		L_{N}	0.988**	0.983**	0.974**	0.984**	0.983**	0.986**	0.988**
	Jumping	L_{Aeq}	0.952**	0.970**	0.962**	0.966**	0.977**	0.971**	0.964**
		L_{AFmax}	0.947**	0.964**	0.957**	0.961**	0.972**	0.965**	0.958**
		L_{N}	0.962**	0.958**	0.946**	0.959**	0.970**	0.968**	0.981**
Sand bag		L_{Aeq}	0.953**	0.961**	0.914**	0.959**	0.965**	0.942**	0.974**
		L_{AFmax}	0.946**	0.954**	0.904**	0.952**	0.958**	0.935**	0.970**
		L_{N}	0.836**	0.832*	0.773*	0.831*	0.863**	0.826*	0.897**
Water bottle		L_{Aeq}	0.991**	0.982**	0.963**	0.984**	0.977**	0.980**	0.971**
		L_{AFmax}	0.988**	0.985**	0.963**	0.986**	0.985**	0.984**	0.981**
		L_{N}	0.944**	0.928**	0.898**	0.931**	0.935**	0.930**	0.946**
Wooden blocks		L_{Aeq}	0.991**	0.982**	0.963**	0.984**	0.976**	0.980**	0.968**
		L_{AFmax}	0.989**	0.985**	0.963**	0.986**	0.985**	0.985**	0.979**
		L_{N}	0.954**	0.952**	0.909**	0.951**	0.966**	0.949**	0.978**

crete slab, but such was not the case in this study with extremely high correlation coefficients. All the correlation coefficients between the child running and jumping and the SNQs were significant for both the tapping machine and the impact ball. The dropping of objects also showed similar tendencies, representing significant correlation coefficients with the standard SNQs and an insignificant difference between the tapping machine and the impact ball.

3.5. Limitations

This study aimed to provide more understanding about the SNQs based on the relationships between standard impact sources and real impact sources in lightweight floor structures. In the present study, two adult walkers (one male and one female) and two children took part in the measurements. However, dynamic impact forces induced by human walking vary considerably across people with different weights and walking patterns [35]. In particular, the children's running and jumping were less consistent than the adults' walking even after training. Therefore, the number of walkers must be increased in the future to cover a wide range of weights and heights. Moreover, only one floor covering was applied to the floor structures in this study. In contrast, Kylliäinen, et al. [15] investigated the impact SPLs with eight floor coverings on a concrete slab and reported huge variations in SNQs and noise ratings across the floor coverings. Thus, adding various floor coverings in different floor structures to examine the effects of floor covering on SNQs and noise ratings would be useful. Furthermore, this study was conducted in a laboratory with suppressed flanking paths. So whether the results would be the same in situ is unknown although flanking transmission tends to be of lees importance at low frequencies in timber-frame constructions [37]. Thus, a comparison of laboratory and in situ circumstance would be worth focusing on. Lastly, the SNQs were developed to compare the objective measures with the subjective responses [6,9]; thus, further research is needed to investigate which SNQs are well correlated with the subjective responses to floor impact noise in lightweight structures.

4. Conclusion

The SPLs from two standardised impact sources (tapping machine and impact ball) and six real sound sources (the footsteps of adults and children and the dropping of objects) were measured on four different lightweight floor configurations with and without carpet covering. The results showed that the floating floor and the suspended ceiling significantly reduced the SPLs at mid and high frequencies. The carpet helped to reduce lightweight impact sounds, whereas the effect of the carpet was insignificant in heavyweight impact sounds. The frequency characteristics of the tapping machine and the impact ball showed similar correlation coefficients with real impact sources between 50 Hz and 1 kHz in one-third octave bands for floor structures with floating floors and/or suspended ceilings. For the floor structures with floating floors or suspended ceilings, the variations of the SNQs for the tapping machine and the impact ball were similar. All the standardised SNQs for the tapping machine and the impact ball were significantly correlated with the noise ratings of the real impact sources. In particular, the SNQs had greater correlation coefficients with the energy-based noise ratings ($L_{A,eq}$ and $L_{A,Fmax}$) than the loudness level L_N. This implies that the standardised SNQs for tapping machine and impact ball assessed the lightweight floor structures adequately considering the realistic situations with different real impact sources. The variations of walking such as walking speed and footwear had little impact on the correlations between the SNQs and the noise ratings. Furthermore, the other real impact sources showed significant correlation coefficients between the SNQs and the noise ratings for both the tapping machine and the impact ball. The findings of this study could be expanded to research into subjective tests in the future to develop new objective SNQs based on the tapping machine and impact ball.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apacoust.2020.107690.

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