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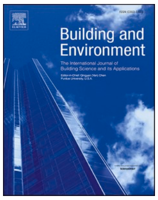

Suitability of standardized single-number ratings of impact sound insulation for wooden floors – Psychoacoustic experiment

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ABSTRACT

Wooden floors usually have worse impact sound insulation (ISI) at low frequencies than concrete floors having the same rating level. Rating level is usually expressed by single-number quantities (SNQs), such as weighted normalized impact sound pressure level $L_{n,w}$. Psychoacoustic research among wooden floors is very limited although a controlled laboratory experiment is the strongest method to point out the most adequate SNQs to be declared for the floors. The purpose of our study was to determine how four standardized SNQs of ISO 717-2, $L_{n,w}$, $L_{n,w} + C_I$, $L_{n,w} + C_{I,50}$, and $L_{iA,Fmax,V,T}$, and a recently proposed SNQ, $L_{n,w} + C_{I,25}$, are associated with the annoyance of natural impact sounds transmitted through wooden floors. Fifteen floors were built in the laboratory based either on cross-laminated timber (heavy) or open box wood (light) slabs. Different coverings and suspended ceilings were applied on these slabs. The ISI was tested within 25–3150 Hz using both tapping machine and rubber ball. Thereafter, five natural impact sounds were recorded for each floor: rubber ball drops, steel ball drops, walking, jumping, and chair pushing. Fifty-two people rated the annoyance of these 75 recorded natural impact sounds in psychophysics laboratory. Annoyance was best associated with $L_{n,w}$ for all the five impact sound types. That is, measurement of ISI within 100–3150 Hz is sufficient from subjective point of view. All four SNQs based on tapping machine explained annoyance better than the SNQ based on rubber ball. Our results can significantly guide the future research, development, and regulations of wooden floors.

1. Introduction

Impact sounds caused by neighbors can be important sources of environmental dissatisfaction in multi-storey apartment buildings. Impact sounds include, e.g., walking, jumping, vacuum cleaning, furniture moving, water gurgle in toilet bowl and shower, and items dropping. To minimize the noise annoyance, it is important to control noise by using such floor constructions that provide sufficient impact sound insulation (ISI).

The ISI of a floor construction can be objectively determined in laboratory conditions according to the international standard ISO 10140-3 [1]. Measurements are based on standardized impact sound sources which are not natural, but their force towards the floor is highly controlled. The standard sources are beneficial in measurement since they produce a constant, strong, wideband structure-borne vibration to the floor. ISO 10140-3 offers two alternative impact sound sources: the tapping machine and the rubber ball. The latter represents a heavy and soft impact source.

The tapping machine is the mandatory impact source in most countries. The tapping machine produces a chain of metal hammer impacts (ten impacts per second). The measurement with the tapping machine provides the normalized impact SPL, L_n [dB], within 1/3-octave frequency bands from 50 to 5000 Hz. The performance of the floor can be summarized from the measured data by three single-number quantities (SNQs) defined in ISO 717-2 [2]: $L_{n,w}$, $L_{n,w} + C_I$, and $L_{n,w} + C_{I,50}$ (abbreviation of $C_{I,50-2500}$).

The measurement with rubber ball provides the standardized maximum impact SPL, $L_{i,Fmax,V,T}$ [dB], within 1/3-octave frequency bands from 50 to 630 Hz. The performance of the floor is summarized using a SNQ, $L_{iA,Fmax,V,T}$, also defined in ISO 717-2 [2]. The use of rubber ball has been justified because the SPL spectrum is closer to the SPL spectrum of walking and children jumping [3]. From scientific point of

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view, it is important to investigate both standardized impact sound sources in parallel.

The main function of a SNQ is to rank various kinds of floors, independent on materials used in different layers, in the correct order of superiority with respect to noise control. The ranking order that a SNQ gives for floors is expected to have the highest possible correlation with the ranking order that people give to the same floors from subjective perspective (i.e., annoyance) when the floors are excited by natural impact sounds. There is clear evidence that standardized SNQs of ISO 717-2 serve that purpose at least for concrete floors when the natural impact sounds are walking with hard shoes, walking with soft shoes, or chair moving [4].

It is well-known that the standardized SNQs are not based on solid scientific evidence. Standard proposals are usually based on consensus agreements within standardization working groups. Final standard proposals are submitted to ballots among international standardization committees. These decisions might be changed with time only if strong scientific evidence about a better SNQ exists and a sufficient political acceptance of new evidence is reached. At this moment, strong scientific evidence regarding concrete floors or wooden floors does not exist.

Ljunggren and Simmons [5] conducted ISI measurements and residential surveys about perceived noise annoyance due to neighbor noises in 38 houses, out of which 17 had lightweight floors (mainly wooden rib slab construction), 11 had cross-laminated timber (CLT) floors, and 10 had concrete floors, respectively. They found that noise annoyance due to impact sounds produced by residents in an upper floor was larger in residential multistorey buildings with wooden floors than in buildings with concrete floors, although, the floors would be equal from an objective point of view (similar $L'_{\mathrm{nT,w}}$ values). Standardized weighted impact SPL, $L'_{\mathrm{nT,w}}$, is a counterpart of $L_{\mathrm{n,w}}$ which is also based on ISO 717-2 but it is intended for field measurements. They analyzed, how well different SNQs of ISI are associated with the annoyance caused by impact sounds among the residents. They investigated the following SNQs: $L'_{\mathrm{nT,w}}$, $L'_{\mathrm{n,Tw}} + \mathrm{C}_{\mathrm{I,50}}$, $L'_{\mathrm{n,Tw}} + \mathrm{C}_{\mathrm{I,25}}$, $L'_{\mathrm{n,Tw}} + \mathrm{C}_{\mathrm{I,20}}$, $L'_{\mathrm{n,Tw}} + \mathrm{C}_{\mathrm{I,AL,25}}$, and $L'_{\mathrm{n,Tw}} + \mathrm{C}_{\mathrm{I,AL,20}}$ (see definitions in **Sec. 2.5**.) They found that $L'_{\mathrm{n,Tw}} + \mathrm{C}_{\mathrm{I,25}}$ (including 25−3150 Hz) correlated best with annoyance caused by neighbor's impact sounds. They recommended that impact SPL should be measured within 25–3150 Hz.

Cross-sectional surveys cannot be used to prove causal relationships since surveys are very sensitive to several biases. First, it is not possible to control nor measure the impact sounds that residents upstairs produce. Second, it is not possible to control the non-acoustic factors that might affect residents' ratings at home even more than the stimulus itself (e.g., attitudes towards the neighbor, expectations about the sound insulation, ownership, and lifestyle in general). Third, residents have uncontrollable masking sound levels at homes (e.g., family members, radio, TV, and fans). Fourth, the ISI measurements are only conducted in few apartments per building, not in every apartment. The ISI values cannot be applied to all apartments of the building since the standard deviation of ISI is very large especially in wooden houses [6]. Fifth, there are several sources of neighbor noise in residential apartments which can confound the annoyance ratings (not only impact sounds from upstairs). These five reasons significantly increase the uncertainty related to both stimulus and perception. This problem was also present in the data of Ref. [5]: completely different mean annoyances were observed in lightweight, CLT, and concrete houses having similar $L'_{\mathrm{nT,w}}$ value. Therefore, an experimental study is needed to test their finding.

Psychoacoustic laboratory experiments do not suffer from uncertainties related to the SPLs of stimulus and background noise. In psychoacoustic experiments, the desired SPL is usually obtained by recording the actual impact sounds for specific floors, whose ISI has been measured. The SPL of sounds presented to the participants can usually be controlled with an accuracy of 1–2 dB L_{Aeq}. That is, the SPL heard by the participant almost perfectly matches with the desired SPL. The background noise can also be perfectly controlled in laboratory experiments and variations in the SPL of background noise cannot confound the outcomes. Furthermore, the between-resident variance of annoyance caused by non-acoustic factors are absent in laboratory experiments. The participants must solely focus on the presented sounds in laboratory conditions. The remaining factors causing between-participant variance in annoyance ratings are, e.g., individual noise sensitivity, motivation, mood, and general response style. In laboratory environment, the absence of all other visual, social, or acoustic stimuli guarantees that the focus on sounds is high, and the differences in individual subject's ratings mostly depend on perceived differences between the experimental sounds.

Vardaxis and Bard [7] reviewed psychoacoustic laboratory experiments related to impact sound insulation. They found 16 papers. Several peer-reviewed papers were identified that investigated how well the standardized and alternative SNQs explain the perceived annoyance of impact sounds through concrete floors so that the psychoacoustic stimulus was based on real recordings and not on SPL simulations. Two studies involved a mixture of wooden and concrete floors [8,9]. Wooden and concrete floors usually have quite different ISI spectra at low frequencies. Therefore, it is justified to expect that the subjectively optimal SNQ for these two floor families might need different spectrum weightings. Thus, it is justified to assess these floor families in separate studies to reach the basic understanding about possible differences between the weighting spectra.

Although the research on wooden floors is strong in general, there are very few psychoacoustic experiments that have involved only built wooden floors. Gover et al. [10,11] found that $L_{\mathrm{n,w}}$ and $L_{\mathrm{n,w}} + C_{\mathrm{I}}$ explained the annoyance produced by walking with socks better than $L_{\mathrm{n,w}} + C_{\mathrm{I,50}}$. They focused on wooden joist floors. Massive wood slabs, such as CLT or LVL slab, were not involved. Moreover, they did not study high-frequency natural impact sounds, nor extended measurements below 50 Hz.

It is well known that the spatial variation of one-third octave band SPLs normal-sized rooms vary a lot below 200 Hz due to room modes (e.g., Ref. [12]). The spatial SPL variation is the strongest, if the transmitted sound contains a tone that matches the frequency of a room mode. The sound radiated by a floor usually has a broadband nature. However, the sound can have a tonal nature if the construction involves a resonance frequency. An example of that is the floating floor resonance, which usually takes place under 200 Hz [13]. In some cases, the A-weighted SPL can be dominated by this resonance and the spatial SPL variation becomes an additional issue of ISI measurement uncertainty. Floating floors and suspended ceilings are frequently used with wooden floor slabs. Therefore, it might be relevant to use more than one recording position also for psychoacoustic recordings. According to our knowledge, the impact sound recordings for previous psychoacoustic experiments have been made using a single position in the receiving room. It is relevant to study, whether the recording position affects the results of a psychoacoustic experiment.

The purpose of our psychoacoustic experiment was to determine how the standardized SNQs based on ISO 717-2, i.e., $L_{\mathrm{n,w}}$, $L_{\mathrm{n,w}} + C_{\mathrm{I}}$, $L_{\mathrm{n,w}} + C_{\mathrm{I,50}}$, and $L_{\mathrm{iA,Fmax,V,T}}$, and the recently proposed SNQ, $L_{\mathrm{n,w}} + C_{\mathrm{I,25}}$, are associated with the annoyance of natural impact sounds transmitted through wooden floors. Another purpose was study whether the results of the psychoacoustic experiment depend on the recording position in the room.

2. Materials and methods

2.1. Overall study design

We conducted a psychoacoustic laboratory experiment, where the participants rated the annoyance of five natural impact sounds transmitted through 15 different wooden *floors* making altogether 75 sounds. The stimuli were obtained in an ISI laboratory, where the 15 floors were built one after the other. For each floor, the ISI was measured, and the natural impact sounds were recorded.

The independent variables of the psychoacoustic experiment were the *sound type* (five alternatives) and the ISI of each floor, described by five selected SNQs. The dependent variable was the *annoyance*.

2.2. Participants

Voluntary persons were reached by sending an advertisement to the student news or email lists of Turku University of Applied Sciences and University of Turku. The requirements for participation were Finnish native language, age between 20 and 40 years, and normal hearing ability. The recruitment letter stated the following information: "*We seek voluntary persons to an experiment, where the task is to listen and evaluate sounds heard in residential dwellings. The sounds are not loud and there is no risk of hearing damage or frightening. The experiment lasts for 1 h and each participant receives a 20-euro gift token after the execution of the experiment*".

The research ethic board of Turku University of Applied Sciences supported the research (Statement 2022-049, 6th Jun 2022).

Fifty-two persons (33 women, 17 men, 2 other) participated voluntarily in the experiment. The participants were between 18 and 42 years old (Mean = 27, SD = 6). Based on the hearing threshold test (**Sec. 2.9**), all participants had normal hearing ability as required in the recruitment.

2.3. Floor constructions

Initially 38 floor constructions (later: floors) were built to the ISI laboratory to create a sufficiently large pool of stimuli. The constructions consisted of load-bearing slab and different toppings. Most of the wooden constructions also involved a suspended ceiling. The pool consisted of 11 wooden floors based on 260 mm CLT slab, 4 wooden floors based on 140 mm CLT slab, 15 wooden floors based on 370 mm open box slab, and 8 concrete floors based on 160 mm steel-reinforced concrete slab. The ISI (see **Sec. 2.4**) was measured, and natural impact sounds (see **Sec. 2.6**) were recorded for these 38 floors. Since the number of experimental sounds in a psychoacoustic experiment must be reasonable, 15 wooden floors were selected from this pool of data to this experiment such that the $L_{n,w}$ values cover the range of ISI regulations between European countries well [14,15]. Rasmussen [14] has surveyed the regulations and the range is from 48 dB (Austria) to 68 dB (Serbia). This range probably represents the regulations well also globally, although, the SNQs applied in different countries vary a lot. Furthermore, it was required that all the 15 floors must have the same floor covering (laminate) because previous psychoacoustic experiments faced challenges in producing feasible stimuli with, e.g., chair pushing when coverings with different kinetic friction were mixed [4,8,13].

The schematic construction drawings of the 15 selected wooden floors used in this experiment are shown in Fig. 1. Detailed structure drawings are shown in Fig. S1−S4 (Supplementary material).

It should be noted that floors O1 and O2 have identical constructions. However, both floors were tested and recorded for separate installations of the floating floor. Floor O2 was built and tested 4 months later than floor O1. This setup allows to analyze the uncertainties related both to objective and subjective assessments of ISI for reproduced constructions.

The load-bearing slabs, toppings, and suspended ceilings were mostly installed by two of the authors, who are experienced in construction work. Screed layers were installed by external contract workers but under the surveillance of these two authors. The screed

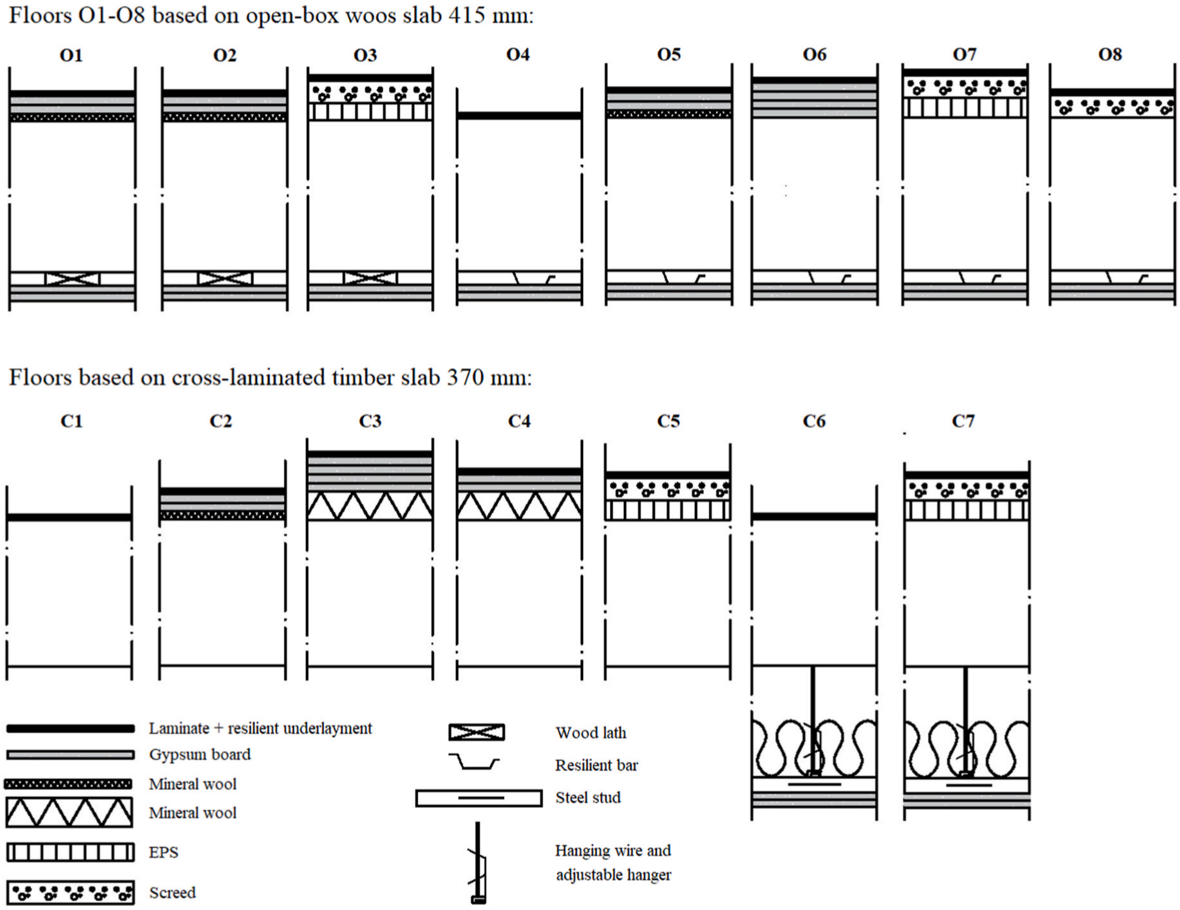

Fig. 1. Schematic section drawings of the 15 investigated wooden floors. The load-bearing slab is indicated with hollow square. Detailed structure drawings are in Fig. S1−S4 (Supplementary material).

thickness varied less than ±2 mm. The screed was cured at 20 °C for at least 14 days. A thin plastic layer was placed below the screed to prevent leakages and to enable the removal of screed without damaging the load-bearing floor.

2.4. *Impact sound insulation measurements*

All fifteen floors were built and tested in the ISI laboratory (Turku University of Applied Sciences Ltd., Turku, Finland) during 2021−2. The section of ISI laboratory is shown in Fig. 2. The dimensions of the test floor were 4.1 × 2.5 m (10.25 m^2).

The normalized impact SPL, L_n [dB], produced by standardized tapping machine (Nor 277, Norsonic Ltd., Norway) was determined according to ISO 10140-3 [1] in 1/3-octave bands within 25–3150 Hz. Although measurements within the range 25–40 Hz are not specified in the standard, and the measurement uncertainty is unknown, the range was included because of scientific reasons. SPL measurements were conducted with sound level analyzer (B&K 2260, Brüel & Kjær Sound & Vibration Measurement A/S, Denmark). As required by the standard, 5 positions of tapping machine were used. For each position 5 fixed microphone positions were used. Positions of the microphone and the tapping machine with respect to each other and room and floor boundaries followed the standard's requirements. Measurement duration in each position was 15 s. Reverberation time measurements were conducted using the interrupted noise method produced by a loudspeaker (Nor 276, Norsonic Ltd., Norway) and an amplifier (Nor 280, Norsonic Ltd., Norway). The decays were stored (Tascam HD-P2, Teac Corporation, Japan) and later analyzed (Nor 840, Norsonic Ltd., Norway).

The standardized maximum impact SPL, $L_{i,Fmax,V,T}$ [dB], produced by rubber ball was determined according to ISO 10140-3 [1] within 1/3-octave bands in the range 25–3150 Hz. The dropping height of the rubber ball (YI-01, Rion Co Ltd., Japan) was 1.000 m from the floor. As required by the standard, four dropping positions of the rubber ball were used. For each position, four fixed microphone positions were used.

The ISI curves of the 15 floors are shown in Fig. 3. The data is also available in open data format [16,17].

2.5. *Inspected single-number quantities*

Five SNQs were inspected:

1. Weighted normalized impact SPL, $\boldsymbol{L_{n,w}}$. It is based on the ISO 717-2 standard [2].

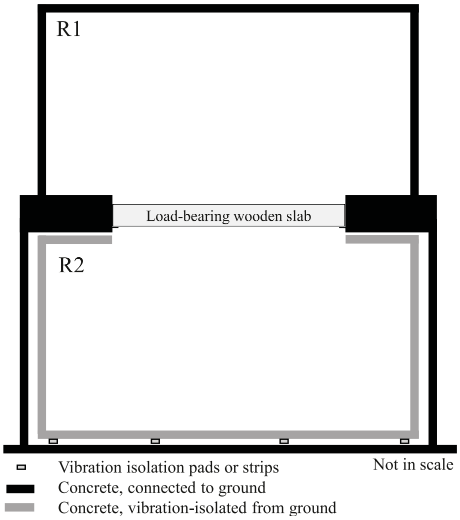

Fig. 2. Principal section drawing of the impact sound insulation laboratory.

2. Weighted normalized impact SPL involving a spectrum adaptation term $C_{I,100}$ within 100–2500 Hz, $\boldsymbol{L_{n,w} + C_I}$. It is based on an informative Annex A of ISO 717-2 [2].
3. Weighted normalized impact SPL involving a spectrum adaptation term $C_{I,50}$ within 50–2500 Hz, $\boldsymbol{L_{n,w} + C_{I,50}}$. It appears in a note of the informative Annex A of ISO 717-2 [2], where it is denoted $L_{n,w} + C_{I,50-2500}$.
4. Weighted normalized impact SPL involving a spectrum adaptation term $C_{I,25}$ within 25–2500 Hz, $\boldsymbol{L_{n,w} + C_{I,25}}$. It is based on Ref. [5].
5. A-weighted standardized maximum impact SPL, $\boldsymbol{L_{iA,Fmax,V,T}}$, within 50–630 Hz. It is based on the normative Annex D of ISO 717-2 [2],

The spectrum adaptation terms of 2–4 are determined by

$$C_{I,M} = 10\cdot\log_{10}\left[\sum_{i=1}^{n}10^{(L_i-X_i)/10}\right] - L_{n,w} \qquad (1)$$

where $X_i = 15$ dB, M is the lowest frequency band of interest (100, 50, or 25), and n is 15, 18, or 21, respectively.

The single-number values of the 15 floors are shown in Table 1. The single-number values were well distributed since there are not many floors having equal values. This is indicated by the small value of D_S, which indicates the standard deviation of the differences between the nearby rank-ordered single-number values of the floors. The distribution of the single-number values for each SNQ is also shown in Fig. S5 (Supplementary material) indicating the smooth distribution of the single-number values.

2.6. *Natural impact sounds*

Two independent studies [4,13] have shown that the subjective ranking order of different floor constructions can be different with different impact sound types. Therefore, it is important to investigate spectrally different natural impact sound types.

Natural impact sounds usually consist of people walking/jumping (low frequency sound), hard items dropping (high frequency sound), vacuum cleaning (high frequency, long-term sound), and furniture moving (broadband frequency, long-term sound). Therefore, seventeen different sound types were recorded for each floor to create a sufficient pool of impact sound data. The impacts were created by standardized tapping machine, standardized rubber ball drops (Rion Impact ball, diameter 178 mm, 2.5 kg, drop heights 250, 500, and 1000 mm), 20-mm-diameter steel ball drops (33 g, drop heights 250, 500, and 1000 mm), 30-mm-diameter steel ball drops (110 g, drop heights 250, 500, and 1000 mm), 50-mm-diameter steel ball drops (511 g, drop height 500 mm), necklace drops (71 g, drop height 1000 mm), normal walking with socks (7 steps, pace 120 bpm), heel walking with socks (7 steps, pace 120 bpm), jumping with socks (140 bpm), chair 1 pushing (5050 g, soft walking pace 110 bpm), and chair 2 pushing (5700 g, walking pace 110 bpm).

Some of the 17 sound types were very loud for some floors (more than 60 dB $L_{A,Fmax}$), so that they were presumed to produce very high annoyance for all 15 floors and very little difference between the floors. On the other hand, some other sound types were inaudible for certain floors. After the analysis of 17 sound types, we could identify 5 *sound types* which represented the broad spectral spread described above. In addition, they were not too loud nor inaudible. The 5 *sound types* chosen to the psychoacoustic experiment, and their abbreviations in brackets, were

- Rubber ball drop from 250 mm height (Rubber ball)
- Steel ball (20 mm) drop from 250 mm height (Steel ball)
- Heel walking with socks (Walking)
- Jumping with socks (Jumping)
- Chair pushing (Chair)

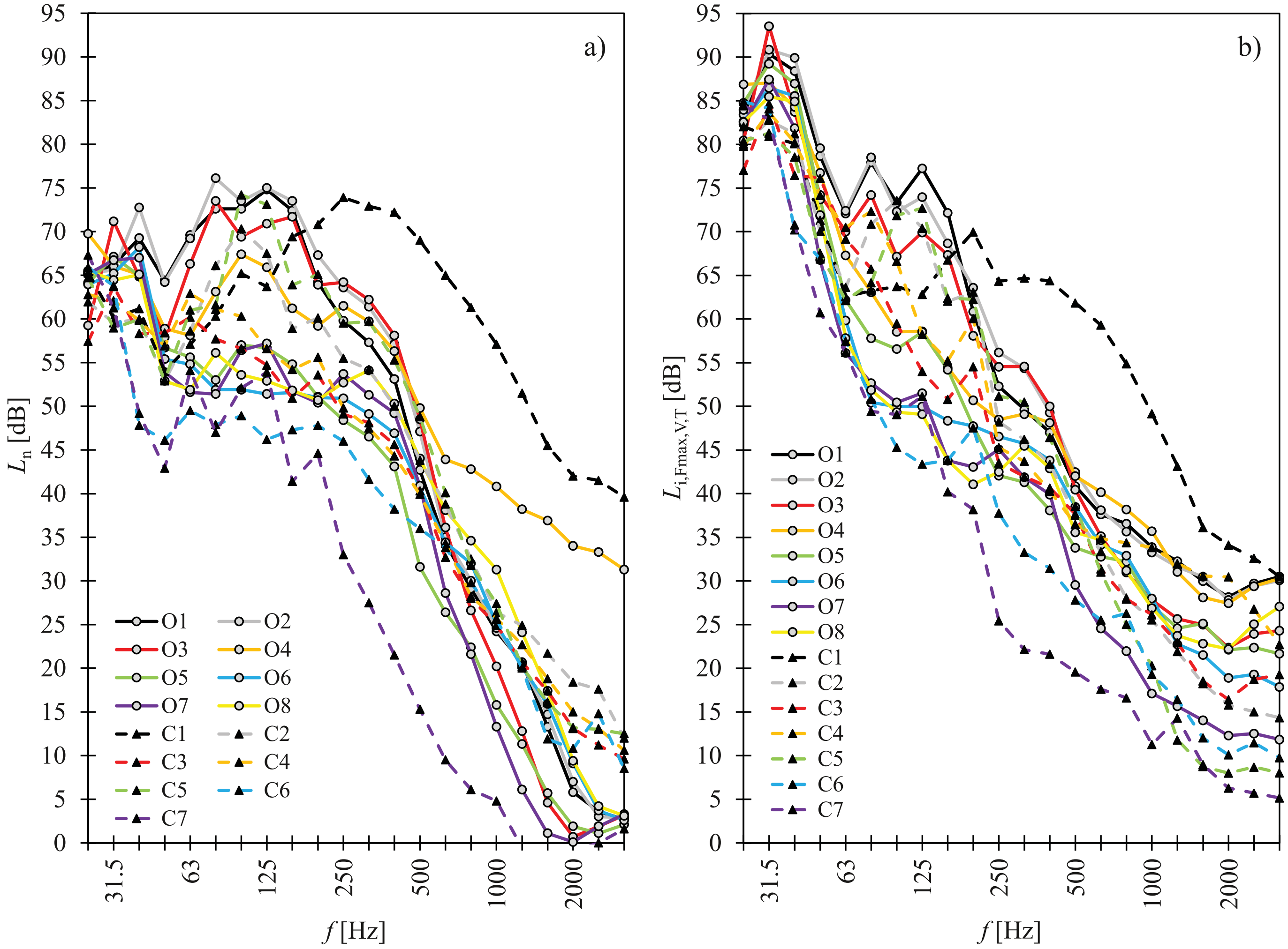

Fig. 3. Test results of impact sound insulation according to ISO 10140-3 as a function of frequency, f, for the 15 floors. A) Normalized impact SPL produced by the tapping machine, L_n. b) Standardized maximum impact SPL produced by the heavy/soft impact source, i.e., rubber ball drops from 1.00 m height, $L_{i,Fmax,V,T}$. Numerical values are given in Table S1–S2 (Supplementary material).

The rubber ball drop has been created to resemble the sound produced by children jumping [18]. The drops were created using the standardized rubber ball (YI-01, Rion Co Ltd., Japan). Drops were always made in the same three positions on the floor. Recording was made for 3 drops and the most representative drop was chosen to the psychoacoustic experiment. The variation between 3 drops was always negligible due to the constant dropping height. The most representative drop was determined to have an A-weighted equivalent SPL closest to the mean of all three drops. The duration of the Rubber ball recording used in the psychoacoustic experiment was 1.0 s. The chosen drop sound recording was looped to produce periodic "one drop per second" (pace 60 bpm) sample in the psychoacoustic experiment. The recorded level of Rubber ball was significantly higher compared to Walking for all 15 floors. To avoid the saturation of the annoyance responses, the level of Rubber ball was reduced by 10 dB for every floor. The duration of Rubber ball sample used in the experiment was 8.0 s.

Steel ball drop represents sound produced by the dropping of a hard item. The drops were always made in the same three positions on the floor as for Rubber ball drops. Other definitions and procedures were the same as for Rubber ball drops above. The duration of the Steel ball recording used in the psychoacoustic experiment was 1.0 s. The chosen drop sound sample was looped to produce a periodic "one drop per second" (pace 60 bpm) stimulus in the psychoacoustic experiment. The duration of Steel ball sample used in the experiment was 8.0 s.

Walking was performed by the same person (male, 52 y, 177 cm, 75 kg), who walked along a single diagonal path (4.8 m) on the floor. A single walkthrough contained seven steps. Walking was strictly paced using a metronome (120 bpm, 2 steps per second). At least 10 successful walkthroughs were recorded for each floor. Either the first or the last step of each walkthrough was removed since it was often different from the six other steps of the walkthrough. The duration of each 6-step walkthrough was 3.0 s. The successful recordings were analyzed. The typical variation between recordings on one floor is shown in Fig. S6 (Supplementary material). The maximum standard deviation of $L_{Aeq,3s}$ was 1.2 dB. Therefore, the reproducibility of the walk impact forces between different floors was not a concern. The most representative recording was chosen to be the sample used in the psychoacoustic experiment. It had a smooth pace, and the $L_{Aeq,3s}$ was close to the mean $L_{Aeq,3s}$ of all ten candidates. The duration of the Walking sample used in the psychoacoustic experiment was 3.0 s.

Jumping was performed by the same person as above. The trajectory of metatarsus in the extreme position of one jump is shown in Fig. S7 (Supplementary material). Jumping was always made in the same position on each floor. Jumping was strictly paced using a metronome (140 bpm, 2.33 jumps second). Jumping was recorded at least 60 s in a row. The recording divided into seventeen 3.4-s-long recordings. The most representative recording was chosen to the psychoacoustic experiment. The most representative recording had L_{Aeq} close to the mean L_{Aeq} of all 17 candidates. The SPL variation between 15 Jumping recordings was smaller than that for Walking recordings. The most representative

Table 1

The single-number values [dB] of impact sound insulation of the 15 studied floors. $L_{n,w}$, $L_{n,w} + C_I$, $L_{n,w} + C_{I,50}$ are based on ISO 717-2 standard [2]. $L_{n,w} + C_{I,25}$ is based on the recommendation of [5]. Under the line, additional information is given. Min and Max are the minimum and maximum values of the single-number quantity. D_e is the difference of these extreme values. D_M is the mean difference between nearest single-number values and D_S is the standard deviation of the 14 differences. The source options are tapping machine, TM, and rubber ball, RB. Range gives the frequency range [Hz] of each SNQ.

	$L_{n,w}$	$L_{n,w} + C_I$	$L_{n,w} + C_{I,50}$	$L_{n,w} + C_{I,25}$	$L_{iA,Fmax,V,T}$
O1	61	64	65	65.6	65
O2	63	64	66	67.1	63
O3	60	61	64	64.4	60
O4	56	57	58	60.4	53
O5	46	47	49	56.3	49
O6	44	44	47	56.5	47
O7	47	47	48	56.8	44
O8	46	46	48	55.6	46
C1	65	65	65	65.3	66
C2	55	58	59	59.4	60
C3	45	46	51	53.6	51
C4	47	49	53	55.2	55
C5	60	62	63	62.9	60
C6	39	40	42	53.3	42
C7	38	42	44	53.8	39
Min	38	40	42	53.3	39
Max	65	65	66	67.1	66
D_e	27	25	25	13.8	27
D_M	1.9	1.8	1.7	1.0	1.9
D_S	2.3	2.0	1.4	0.8	1.3
Source	TM	TM	TM	TM	RB
Range	100–3150	100–3150	50–3150	25–3150	63–630

recording was chosen to be the sample used in the psychoacoustic experiment. The level of Jumping was reduced by 5 dB for every floor. The reason was the same as for the Rubber ball above. The duration of the Jumping sample used in the psychoacoustic experiment was 3.4 s.

Chair pushing was performed by pushing the same chair (chair 2 above), along a diagonal path on the floor. Pushing was made by the same person as above and always along the same path. The chair's legs were equipped with hard rubber tips, which resulted in reasonably stable structure-borne dragging sound. The speed of pushing was controlled by using a constant pace of walking (110 bpm metronome, nine steps along the diagonal). Special care was made to avoid walking to be louder than the chair pushing stimulus. For each floor, recording was made for 10 walkthroughs. The SPL variation between 10 Chair recordings was smaller than that for Walking samples discussed above. The most representative chair pushing recording was chosen to be the sample of the psychoacoustic experiment. This sample had the L_{Aeq} close to the mean L_{Aeq} of all 10 Chair candidates. The duration of the Chair sample used in the psychoacoustic experiment was 4.6 s.

The positions of the natural impact stimuli on the floor were always the same. The walking path of Walking and Chair pushing, dropping positions of Steel ball and Rubber ball, and Jumping position are shown in Fig. S8 (Supplementary material).

The impact sounds were recorded in two positions, A and B, in the ISI laboratory, because our purpose was to determine whether the psychoacoustic findings depend on the recording position. The locations are shown in Figs. S9–S10 (Supplementary material). The impact sounds were presented to the floor in the source room R1 (Fig. 2) and recording was made in the receiving room R2 under the floor (Fig. 2). The reverberation time of the receiving room was shortened during recordings of natural impact sounds because reverberation time in apartments is usually around 0.5 s while it is exceptionally long in reverberation room without any treatment. Similar shortening of reverberation time during natural impact sound recordings was made also by Refs. [4,13]. The shortening was made with additional absorbers, which were distributed to walls, corners, and the floor. Details are given in Fig. S9−S10 (Supplementary material). The reverberation times of the receiving room in the recording positions are shown in Fig. 4. The values conform very well with the mean value of 207 furnished apartment rooms reported by Ref. [19]. The SPL of background noise was 15.7 dB L_{Aeq} during the recordings. The SPL within 20–5000 Hz was under the hearing threshold of normal-hearing human as shown in Fig. S11 (Supplementary material).

Two-channel recordings were made within 20–20.000 Hz using two omnidirectional condenser microphones (G.R.A.S. 26 AK, GRAS Sound & Vibration, Denmark) and Rion DA-21 Data recorder (Rion CO., LTD, Japan). The recorder was located upstairs where the impact sounds towards the floor were created.

Analyses of the recordings and the selection of samples for the psychoacoustic experiment were made with a custom-made analysis program which enables detailed analyses of unweighted equivalent SPL, L_Z, and the unweighted maximum Fast time-weighted SPL, $L_{Z,Fmax}$ for any desired length or moment of the recording (Matlab R2015a, Mathworks Inc., USA). A 100 ms fade-in and 100 ms fade-out were added to the sounds (Adobe audition 2021, Adobe Audio Team, USA) to enable smooth looping of the sounds. This did not have any impact on the SPLs, since the looping was made during faint moments of the stimulus.

2.7. Preparation of experimental sounds

The natural impact sounds recorded in the ISI laboratory were presented to the participants using open-back, circum-aural headphones (Beyerdynamic DT 1990, Beyerdynamic GmbH & Co, Germany). According to the manufacturer, their frequency response was flat within 20–5000 Hz (±2 dB). This frequency range was critical, since the recorded impact sounds were inaudible above 5000 Hz.

The signal from the computer to the headphones was provided via a sound card (Roland Rubix22, Roland Corp., Japan). The sounds were presented in mono (same microphone signal in left and right ear, microphone signal A in experiment A and microphone signal B in experiment B) within 20–5000 Hz. The SPLs presented by headphones were measured using the head-and-torso simulator (HATS, B&K 4100, Brüel & Kjær Sound and Vibration Measurement A/S, Denmark), microphone power supply (B&K 2804, Brüel & Kjær Sound and Vibration Measurement A/S, Denmark) and Sinus Soundbook MK2 (SINUS Messtechnik GmbH, Germany).

The target of the audio preparation was to reach the same SPLs in diffuse field (outside the ear) as measured in the ISI laboratory. Two simultaneous criteria regarding the difference between target SPL and measured SPL had to be fulfilled:

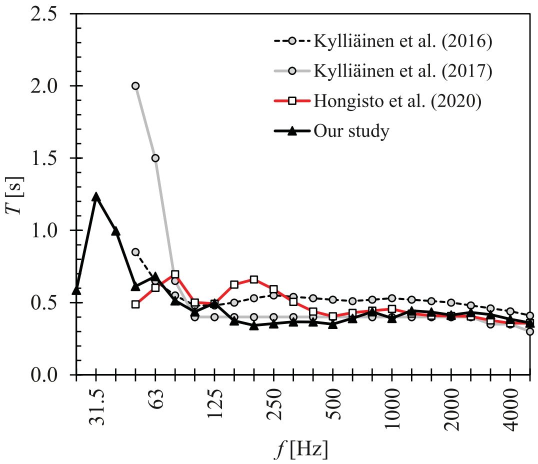

Fig. 4. Reverberation time in the impact sound insulation laboratory during the recordings of natural impact sounds. A comparison with three previous studies is made.

- L_{Aeq} shall not deviate more than 1.5 dB:
- one-third octave band levels shall not deviate more than 3.0 dB within 20–500 Hz and more than 5.0 dB within 630–5000 Hz.

Larger error at high frequency bands was accepted, because the SPL of stimulus was so close to the SPL of background noise in the psychoacoustics room. SPLs above 500 Hz were usually inaudible or at least 20 dB fainter than the most dominant one-third octave bands and this deviation remained insignificant from auditory point of view.

Although the quality of above-mentioned playback device was high, the frequency response was not flat. The frequency response was determined by playing pink noise (Spectrum 1, flat SPL within 20–5000 Hz) to the headphones and measuring the outcome (Spectrum 2) using the HATS. The difference between Spectra 1 and 2 defined the frequency response of the playback system. A spectrum correction (opposite of frequency response) was applied to all test sound samples recorded in the ISI laboratory. The spectrum correction was made in one-third octave bands (Adobe audition 2021, Adobe Audio Team, USA). After the spectrum correction, the spectrum of each test sound sample was measured to assure that the operation led to a result that fulfilled the two criteria above. Further adjustments in the sound samples were made using 1/3-octave filters (Matlab).

All SPL measurements in the psychoacoustics laboratory were conducted using the microphones located in the ear channel of the HATS. The pinna amplifies the sound. The SPL in the ear channel is 1–11 dB higher within 800−10.000 Hz compared to the SPL incident on the pinna, i.e., what prevails in diffuse field (outside the ear). Therefore, the diffuse field correction filter to the measurement results obtained with the HATS was applied to remove the amplification effect and to obtain the SPL that prevails in diffuse field. This corresponds to the SPL that prevailed in the ISI laboratory. The diffuse field correction was made in 1/3-octave bands in analysis phase.

2.8. Psychoacoustics laboratory

The psychoacoustic experiment was conducted in a sound-proof room which is specially designed for psychophysical experiments. The layout is shown in Fig. 5. The SPL of background noise in the room was 14.3 dB L_{Aeq} between 20—10,000 Hz. The SPLs were below the hearing threshold level of ISO 226 between 20—5000 Hz as shown in Fig. S11 (Supplementary material). Background noise was measured using the HATS when the headphones were on. The room temperature was within 21–23 °C during the experiments. The air quality was good because the fresh air inlet rate was approximately 20 l/s. Lighting level was approximately 400 lux on the table level which meets the recommendations for office work.

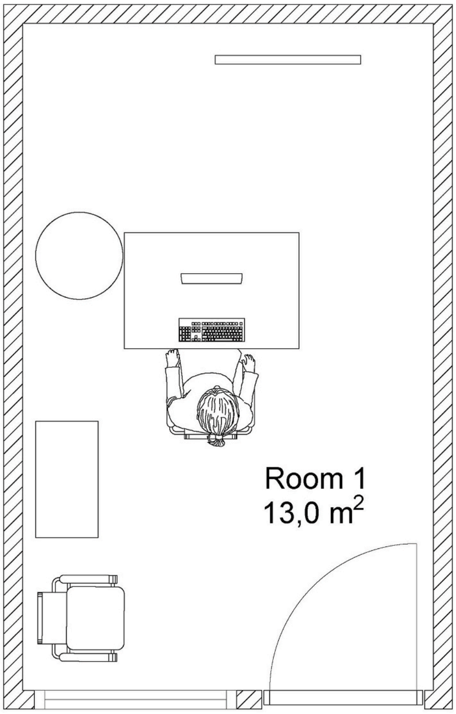

Fig. 5. Layout of the psychophysics laboratory. A photograph is shown in Fig. S12 (Supplementary material).

2.9. Psychoacoustic experiment

The experiment was conducted between August and October 2022. One participant was tested at a time. The experiment took approximately 75 min per person.

The sounds were presented to the participants and their annoyance responses were collected using a program coded in Python. The program was running on a computer located outside the test room to avoid any background noise from the computer.

The experiment consisted of seven phases. The participant was given information about the phases of the experiment, the participant read the informed consent form and signed it (phase 1). The initial questionnaire (phase 2) gathered participants' age and gender. The hearing ability test (phase 3) was performed using the Hughson-Westlake method in frequencies 250, 500, 1000, 2000, and 4000 Hz in both ears (Micromate 304, Madsen Electronics Ltd., USA). The test was carried out to check that the participant's hearing ability was normal. Normal hearing was defined so that the pure-tone thresholds did not exceed the normal hearing threshold curve by more than 20 dB in any of the frequencies. All the participants appeared to have a normal hearing ability. The familiarization phase (phase 4) let the participants become familiar with the full range of experimental sounds. Phase 4 consisted of 10 impact sounds, which included the quietest and the loudest sound of every *sound type*. The sounds were separated from each other by 1 s silence. The participants were not yet given the possibility to rate the sounds. The rehearsal phase (phase 5) consisted of the annoyance rating of 15 sounds which included the quietest, midmost, and the loudest sound of every *sound type*. Now, the participants were allowed to rate the sounds, but these ratings were not analyzed. The first experimental phase (phase 6, Experiment A) took approximately 25 min. The participants rated altogether 80 sounds recorded in position A in the ISI laboratory. After phase 6, the participants were given the opportunity to take a small recess (phase 7). Phase 8 was the Experiment B, in which the participants rated 80 sounds recorded in position B in the ISI laboratory. In phase 9, the participants were given the gift token. If they had further questions, only general answers were given.

Because the five *sound types* were very different and their mean levels were different from each other, it was not feasible to present all experimental sounds in a randomized order in phases 6 and 8. Instead, the experimental sounds were presented in 5 blocks, i.e., one block for each *sound type*. Each Block contained 16 sounds, and each Block represents one *sound type*. The first sound was always a dummy sound. It was used to orientate the participant to the new *sound type*. The rating of dummy sound was not used in the analysis. Dummy sound was followed by 15 experimental sounds (15 floors) having the same *sound type*. Dummy sound was always chosen from floor C2 because it represented the mean L_{Aeq} of all investigated *floors*.

For every participant, different orders of both *sound type* (Blocks) and floor were used. This way, possible bias due to order effects was minimized.

The dependent variable of the psychoacoustic experiment was *annoyance*. To make the ratings closer to a real residential situation, the participants were given the following context advice in phases 4–8: "*When the sound is playing, imagine you are alone at home in an apartment building in complete peace. You are reading a magazine or a book or browsing* *the internet and you start hearing noises from the apartment upstairs.*" The annoyance was measured with question: "*How much does the sound disturb, annoy, or bother you*?" Annoyance was rated using the 11-step numerical response scale of ISO/TS 15666 [20], where the extremes were also verbally labeled (0 Not at all, 10 Extremely much). In addition, there was a separate option "*I do not hear the sound.*" If that option was chosen, annoyance could no longer be rated. These inaudible sounds were identified by storing an annoyance value "-1" in the output data. We counted the number of participants reporting inaudible sounds for each experimental sound to assess the feasibility of the SPL range. However, in the analysis of SNQs, the "-1" values were transformed to "0" since the inaudible sounds do not annoy at all.

Participants were told to use the whole response scale and to try to make the ratings consistently. To encourage the use of the whole response scale, the participants were advised in phases 5, 6, and 8 that if the sound is among the least annoying ones, options 0 or 1 are chosen. Opposite to that, options 9 or 10 are chosen if the sound is among the most annoying ones.

In phases 6 and 8, each sound was played for 8 s (forced minimum listening time) before the annoyance rating scale appeared on the screen. During this 8-s period, the sentence "*You hear a sound like this.*" Was only shown on the display to make the participant focus on the sound instead of the rating. Thereafter, the annoyance rating question appeared on the screen. The sound was repeatedly looped until the response was given.

2.10. Statistical analyses

The total number of inaudible sounds was 60 in Experiment A and 73 in Experiment B. Since both experiments contained 4160 ratings, it means that 1.4−1.7% of sounds were inaudible. Inaudible sensations were recoded to *annoyance* rating 0 in the subsequent analyses.

Outlier analyses of both experiments A and B were conducted using the method documented by Ref. [21]. It inspects three types of response biases at the same time: A. correlation coefficient between individual's response and mean of 52 responses (mean was 0.81); B. sum of squared difference between individual's response and mean of 52 responses (mean was 300); C. number of responses deviating from the mean of 52 responses more than 4 units (mean was 3). Eight participants (6 in Expt. A, 4 in Expt. B) were identified for which type C bias occurred for more than 10 responses out of 75 responses (11−25 times). Despite of this, the responses of these outlier candidates correlated reasonably ($r > 0.46$) with the mean annoyance of 52 participants. This suggests that these candidates had slightly uncertain or carefree response style, but they did not respond randomly in the big picture. The removal of these outlier candidates did not essentially affect the mean annoyance ratings, correlation coefficients, nor the conclusions regarding the ranking order of SNQs. The reported results are, therefore, based on the responses of all 52 participants.

The main analysis concerns the assessment, how the single-number values of 15 floors explain the *annoyance* produced by a specific *sound type* (5 alternatives) presented on these 15 floors. The analysis between the single-number values of 15 floors and mean *annoyance* of 52 participants was made using Pearson's correlation coefficient, r_P. The *annoyance* responses were normally distributed for most of the 75 sounds in both Experiments (see Fig. S13 in Supplementary material). In Experiments A and B, normal distribution criteria (skewness, kurtosis) were slightly violated only for 4 and 8 stimuli, respectively. Violation occurred for the faintest (mean annoyance below 1.5) or the loudest (mean annoyance above 9.5) sounds. Normal distribution is almost impossible to achieve close to the extremes of numerical response scales. Therefore, mean of 52 participants was found to be a feasible descriptor of *annoyance* data. Visual graphs depicting the correlation analysis method are shown in **Sec. 3**. Since our correlation analysis was based on mean *annoyance*, and mean *annoyance* was available for 15 floors ($n = 15$), r_P values exceeding 0.51, 0.64, and 0.76 are statistically significant with 95% ($p < 0.05$), 99% ($p < 0.01$), and 99.9% ($p < 0.001$) probability (2-way analysis), respectively. Since correlation analysis quite easily reaches the lowest significance level ($p < 0.05$), we applied 99% probability as the limit for significance ($p < 0.01$). The existence of statistically significant differences between correlation coefficients was tested by the method of Winkle et al. (1988). The tests were made within each *sound type* for all 10 pairs of SNQs. The significance level was $p < 0.05$ (one-tailed).

The study contained two successive experiments, A and B. Both of them involved the same 75 impact sounds simultaneously recorded in different positions A and B in the receiving room. The correlation analyses were conducted separately to Experiments A and B instead of averaging the *annoyance* responses between the Experiments, to see whether the recording position affects the outcomes of the psychoacoustic experiment. The differences between the *annoyance* ratings in Experiments A and B were investigated using paired sample *t*-test (two-tailed).

3. Results

The overall A-weighted equivalent SPL, L_{Aeq}, of experimental sounds is shown in Table 2. The values ranged within 17.8–57.4 dB. Furthermore, the mean SPLs of *sound types* did not differ very much which suggests that the design of the stimulus was successful. The range of SPLs obtained with 15 floors significantly depended on *sound type*. The range was even 39.6 dB for Steel ball while it was only 12.2 dB for Walking. Therefore, it was expected that the mean *annoyance* ranges are not similar over *sound types*.

The mean *annoyance* ratings for the 75 experimental sounds of Experiment A are collectively shown in Fig. 6. The subjective response data confirms the expectations above based on L_{Aeq}: the range of mean *annoyance* is the largest for Steel ball and the smallest for Walking.

The mean and 95% confidence intervals of *annoyance* responses in Experiments A and B are compared in Fig. 7 for the 75 experimental sounds. The agreement between the mean *annoyance* ratings in Experiments A and B was reasonably good. The correlation coefficient between the mean *annoyances* of Experiments A and B was 0.966. However, the mean *annoyance* of Experiments A and B differed from each other significantly ($p < 0.05$) for 30 sounds out of 75. These sounds are indicated in Fig. 7. The difference was usually statistically non-significant when the difference of the mean annoyance was less than 0.50. The mean *annoyance* of all 75 sounds of Experiment A was, on average, 0.39 units higher than in Experiment B. The maximum difference was 2.13 units (C4_Jump). Considering the facts that the sounds of Experiment A and B were recorded in different position in the receiving room, and their sound levels were slightly different (Table 2), this result is expected.

Our main research questions dealt with five SNQs: $L_{n,w}$, $L_{n,w} + C_I$, $L_{n,w} + C_{I,50}$, $L_{n,w} + C_{I,25}$, and $L_{iA,Fmax,V,T}$. The Pearson's correlation coefficients between the mean *annoyance* and single-number values of 15 *floors* are shown in Table 3 for each *sound type* in Experiments A and B. In addition, the mean r_P over all *sound types* is given to facilitate the overall assessment.

The correlation coefficients were 0.01–0.14 units higher in Experiment B. The increment was the largest for *sound type* Jumping and the smallest for *sound type* Steel ball. Furthermore, the standard deviations of *annoyance* ratings for the 75 sounds were on average 4% larger in Experiment A than in Experiment B. These findings suggest that the learning process during Experiment A led to more consistent ratings in Experiment B.

Fig. 8 illustrates the linear correlation between three interesting SNQs ($L_{n,w}$, $L_{n,w} + C_{I,50}$, and $L_{n,w} + C_{I,25}$) and mean *annoyance* in Experiment B. Similar illustrations concerning Experiment A are shown in Fig. S14 (Supplementary material).

It is notable in Table 3, that all r_P values are statistically significant for *sound types* Rubber ball and Steel ball in both Experiments. Opposite

Table 2

The A-weighted equivalent SPLs, $L_{\mathrm{Aeq,T}}$, for the 75 experimental sounds in Experiments A and B. The durations T depended on the *sound type* as explained in Sec. 2.5. Abbreviations of *sound types*: RB Rubber ball, SB Steel ball, W Walking, J Jumping, C Chair.

Floor	RB	RB	SB	SB	W	W	J	J	C	C
	A	B	A	B	A	B	A	B	A	B
O1	38.0	37.1	37.3	38.4	36.8	35.7	39.8	37.1	31.4	32.7
O2	39.5	37.2	38.9	39.7	39.6	38.1	40.9	38.8	34.7	32.7
O3	34.0	32.4	35.3	35.0	34.6	34.1	35.0	33.4	29.4	31.3
O4	37.5	33.9	38.1	36.1	37.2	34.7	38.2	35.0	37.5	35.4
O5	35.8	32.2	22.1	22.7	34.6	32.3	38.7	35.6	32.5	30.3
O6	35.1	32.0	26.7	27.7	34.9	32.7	39.6	36.6	24.8	22.7
O7	33.4	30.6	26.4	25.1	35.0	33.1	42.3	39.4	33.6	31.5
O8	33.3	30.3	30.0	29.5	33.5	30.9	36.3	33.5	30.9	27.8
C1	32.9	35.3	56.7	57.4	28.7	26.3	31.2	29.5	41.7	42.9
C2	31.6	30.2	30.4	32.4	29.7	28.2	32.2	30.6	30.2	29.8
C3	29.6	25.4	28.0	30.0	30.7	25.9	35.0	29.0	25.6	25.9
C4	32.6	28.7	29.2	29.2	31.7	27.8	32.4	27.0	23.6	24.4
C5	29.9	29.2	32.5	33.5	30.1	29.3	27.9	26.6	28.6	30.1
C6	28.1	26.8	24.2	25.2	27.7	26.6	23.5	21.7	21.6	20.7
C7	26.6	25.1	18.0	17.8	27.2	26.1	21.8	19.7	18.8	20.1

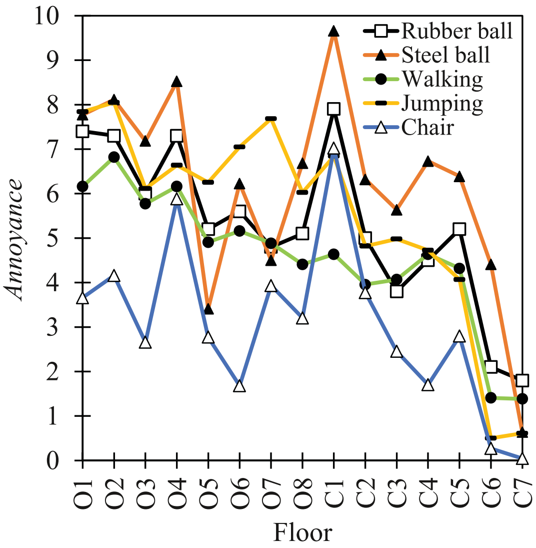

Fig. 6. The mean *annoyance* of 52 participants for the 75 experimental sounds (15 floors combined with 5 *sound types*) in Experiment A.

to that, none of the r_P values was statistically significant for *sound type* Jumping in Experiment A. However, the r_P values became significant for *sound type* Jumping in Experiment B except for $L_{\mathrm{iA,Fmax,V,T}}$. The r_P value of $L_{\mathrm{iA,Fmax,V,T}}$ did not reach statistical significance in Experiment A for *sound type* Walking unlike the other SNQs. Similarly, the r_P value of $L_{\mathrm{n,w}} + C_{\mathrm{I,25}}$ did not reach statistical significance for *sound type* Chair in Experiment unlike the other SNQs. On the other hand, all r_P values were statistically significant for *sound types* Chair and Walking in Experiment B.

Statistically significant differences were not found between the r_P values of the SNQs within any *sound type* both in Experiment A and B. However, it is clear from Fig. 8 and Fig. S13, and abovementioned analysis of the statistically significant r_P values, that there are very clear differences between the SNQs. Therefore, it is justified to cautiously question or promote certain SNQs based on our results, and to suggest if certain SNQs are equally good.

4. Discussion

4.1. Main results

The main purpose of our study was to determine how five SNQs ($L_{\mathrm{n,w}}$, $L_{\mathrm{n,w}} + C_{\mathrm{I}}$, $L_{\mathrm{n,w}} + C_{\mathrm{I,50}}$, $L_{\mathrm{n,w}} + C_{\mathrm{I,25}}$, and $L_{\mathrm{iA,Fmax,V,T}}$) are associated with the noise annoyance of natural impact sounds transmitted through wooden floors. To solve this research question, we conducted an extensive psychoacoustic experiment involving five spectrally different natural impact sound types recorded from fifteen wooden floors.

The main results of our work are shown in Table 3. It suggests that mean *annoyance* of impact sounds was best associated with $L_{\mathrm{n,w}}$ when all five *sound types* and both Experiments A and B are simultaneously considered. There were two exceptions in Experiment B where $L_{\mathrm{n,w}}$ was not superior. $L_{\mathrm{n,w}} + C_{\mathrm{I,25}}$ had the highest r_P for *sound type* Walking and $L_{\mathrm{iA,Fmax,V,T}}$ had the highest r_P for *sound type* Steel ball. However, the lead over $L_{\mathrm{n,w}}$ was marginal (under 0.02 units).

When all five *sound types* are simultaneously considered (means of Table 3), neither $L_{\mathrm{n,w}} + C_{\mathrm{I}}$, $L_{\mathrm{n,w}} + C_{\mathrm{I,50}}$, nor $L_{\mathrm{n,w}} + C_{\mathrm{I,25}}$ provided any significant benefit over $L_{\mathrm{n,w}}$. The finding suggests that, when the assessment of subjective perception of impact sound insulation is under main concern, measurements in the range 50–80 Hz are not necessary to measure for wooden floors as $L_{\mathrm{n,w}} + C_{\mathrm{I,50}}$ $L_{\mathrm{n,w}} + C_{\mathrm{I,25}}$, and $L_{\mathrm{iA,Fmax,V,T}}$ presume. Furthermore, it is even less justified to measure frequencies 25−40 Hz as $L_{\mathrm{n,w}} + C_{\mathrm{I,25}}$ presumes.

Ref. [22] depicted the process of impact sound insulation regulations in Sweden. $L'_{\mathrm{n,w}} + C_{\mathrm{I,50}}$ replaced $L'_{\mathrm{n,w}}$ in Swedish building regulations in 1998. In 2015, voluntary target values were based on $L'_{\mathrm{n,w}} + C_{\mathrm{I,AkuLite,20}}$ requiring normalized impact SPL measurements within 20–3150 Hz. In 2018 [23], $L'_{\mathrm{n,w}}$ was replaced by $L'_{\mathrm{nT,w}} + C_{\mathrm{I,50}}$ also in Finland. The decision was made because it was expected that the Swedish choice was justified. In addition, the psychoacoustic experiment of Ref. [4] based on concrete floors found that $L'_{\mathrm{n,w}} + C_{\mathrm{I}}$ and $L'_{\mathrm{n,w}} + C_{\mathrm{I,50}}$ explained annoyance caused by natural impact sounds (walking with hard shoes, walking with soft shoes, chair moving) almost equally well and slightly better than $L'_{\mathrm{n,w}}$.

Our results suggest that the abovementioned Swedish and Finnish decisions related to the importance of 50–80 Hz for wooden floors were not based on solid scientific evidence since our results question the absolute necessity of measuring these frequencies. Most of European countries still use SNQs based on ISI measurements within 100–3150 Hz [14]. Based on our experimental results, the frequency range 100–3150 Hz could be sufficient for wooden floors.

Our results can also be interpreted in an opposite way: choosing $L_{\mathrm{n,w}} + C_{\mathrm{I,50}}$ or $L_{\mathrm{n,w}} + C_{\mathrm{I,25}}$ instead of $L_{\mathrm{n,w}}$ might not be a totally wrong choice. This interpretation is justified since the mean r_P values of $L_{\mathrm{n,w}} + C_{\mathrm{I,50}}$ or $L_{\mathrm{n,w}} + C_{\mathrm{I,25}}$ were only 0.05 unit smaller than for $L_{\mathrm{n,w}}$ and the r_P values did not differ from each other statistically significantly. However, it is very questionable to choose such SNQs which include frequencies that evidently do not improve the association between objective and subjective assessments of noise. Furthermore, international measurement

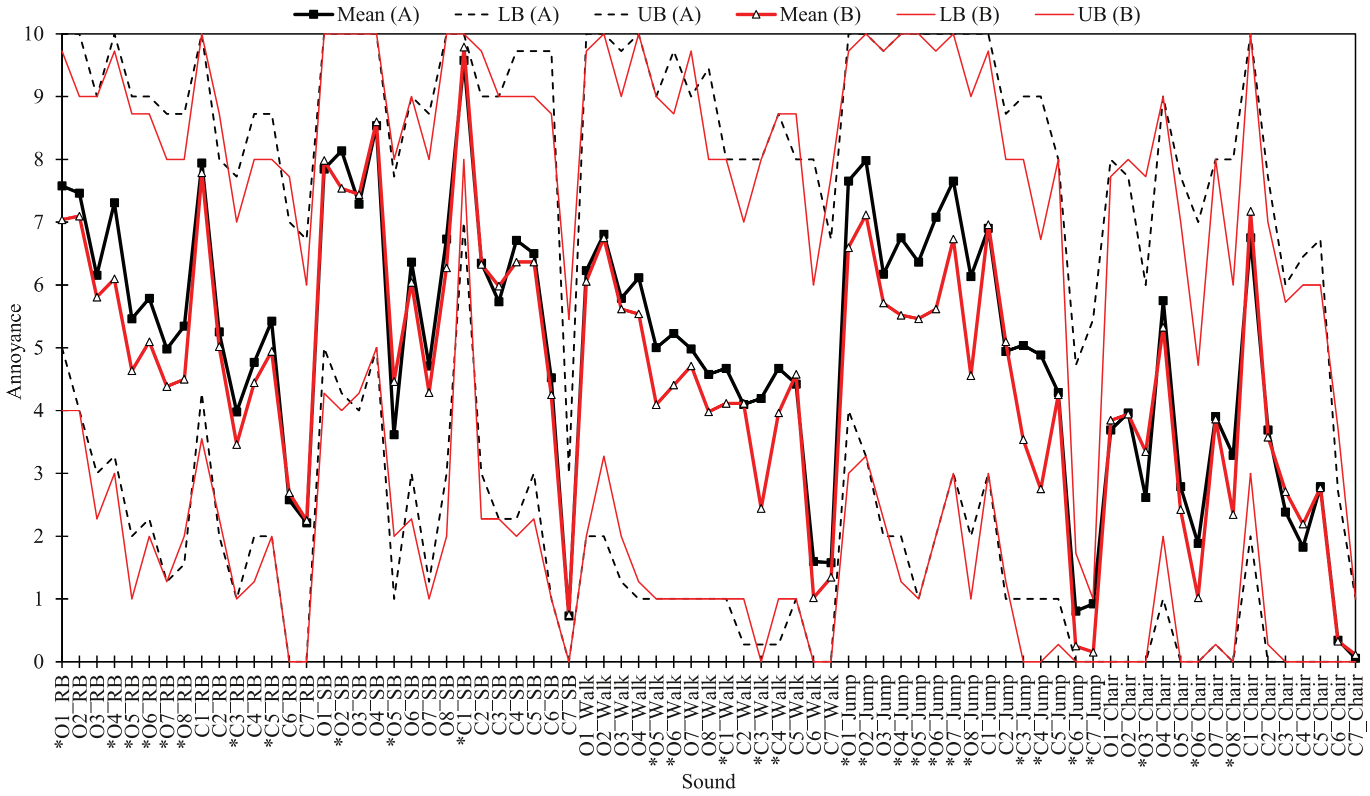

Fig. 7. Basic statistics of *annoyance* of 52 participants for the 75 experimental sounds in Experiments A (black lines) and B (red lines) with mean (M), upper bound of 95% confidence interval (UB) and lower bound of 95% confidence interval. Asterisk* in sound name depicts that the difference between Experiments A and B was statistically significant. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

standards do not currently support the frequency range 25–40 Hz, mostly because the measurement uncertainty under 50 Hz is unknown and reverberation time measurements are uncertain [24].

Our results question the cross-sectional residential survey findings of Ref. [5], who proposed that ISI measurement of wooden floors should include frequencies 25−80 Hz and $L_{n,w} + C_{I,25}$ should be used instead of $L_{n,w}$ or $L_{n,w} + C_{I,50}$. It is important to notice that the methodologies of their and our study are completely different. Our data was obtained in highly controlled acoustic conditions, where the SPL of both impact sound stimulus and background noise were exactly known and the ISI of the floor constructions were precisely known. The recordings were made in the same ISI laboratory where the floors were also tested. The participants focused on the acoustic stimulus only, and effects of non-acoustic factors confounding individual annoyance responses at home (see **Sec. 1**) were minimized. Therefore, our results provide stronger scientific evidence related to auditory perception than the cross-sectional study of Ref. [5]. In general, cross-sectional residential survey method is not adequate method to assess different SNQs from auditory point of view. On the other hand, cross-sectional residential surveys are necessary in assessing, which target value levels (in decibels) should be used for a specific SNQ to reach a certain level of residential satisfaction. In our opinion, this assessment cannot be reliably made using laboratory experiments. Therefore, both laboratory and field research are needed in the design of sound insulation regulations.

Although our experiment is among the largest controlled laboratory experiments in this field, more research is needed. Unlike in natural sciences, human factor research requires several studies before strong scientific evidence can be pointed out. Therefore, further independent scientific evidence regarding the adequacy of these five SNQs is needed.

Further analysis is also needed about the suitability of alternative SNQs studied by, e.g., Ref. [3] for rubber ball, and Refs. [4,5] for tapping machine. Due to the large amount of the alternative SNQs, they were deliberately excluded from the current study.

We did not expect these results since it is generally believed that wooden floors suffer from poor ISI at low frequencies. We expected that $L_{n,w}$ might be well associated with the annoyance of Steel ball drop since it has similar high-frequency character as the tapping machine. Based on the literature, we believed that the annoyance of low-frequency sounds might be better explained by $L_{iA,Fmax,V,T}$. In advance, the findings of Ref. [5] about the importance of frequencies 20−40 Hz sounded logical. However, beliefs and opinions, even if they would sound extremely sound, should not define what SNQs should be recommended for voluntary target values, such as Ref. [15], or national building regulations. Scientific evidence from our experiment is the broadest so far related to wooden floors. Therefore, our results could serve as an important guidance in future academic research and, in the SNQ choices of target values.

Our results suggest that the natural impact sounds produced on wooden floors are so loud at and above 100 Hz one-third octave band, that subjective rating is mainly based on these frequencies. Although the unweighted SPLs would be higher below 100 Hz than above it, the role of frequencies below 100 Hz seem not to be so critical for perception. A feasible explanation is that human loudness sensation below 100 Hz reduces by 6 dB or more every time when frequency is reduced by one-third octave (see hearing threshold level in Fig. S11 in Supplementary material). The SPLs produced by natural impact sounds seldom increase so steeply when frequency reduces from 100 to 25 Hz. Because of that, the loudness within 100–200 Hz is probably higher than within 25–80 Hz. This is one potential explanation why $L_{n,w}$, which covers only 100−3150 Hz, was sufficient.

It would be important to know more precisely, which frequencies participants found the most important in our experimental data. In a follow-up study, we are planning to analyze how different psychoacoustic metrics related to the sounds *per se* (instead of the SNQs of ISI) explain the annoyances of our experiment. For example, Ref. [3] found that Zwicker's percentile loudness (N5) and arithmetic average of octave

Table 3

Pearson's correlation coefficients, r_P, between five objective SNQs of ISI and subjective *annoyance* (mean of 52 participants) for five *sound types*. a) Experiment A. b) Experiment B. The SNQ having the highest r_P is bolded. Values exceeding 0.640 (excluding MEAN) are statistically significant with 99% probability ($p < 0.01$).

a)

Sound type	$L_{n,w}$	$L_{n,w} + C_I$	$L_{n,w} + C_{I,50}$	$L_{n,w} + C_{I,25}$	$L_{i,A,FMax,V,T}$
Rubber ball	**0.859**	0.813	0.809	0.837	0.786
Steel ball	**0.798**	0.743	0.755	0.706	0.791
Walking	**0.691**	0.649	0.679	0.680	0.633
Jumping	**0.591**	0.530	0.544	0.572	0.526
Chair	**0.745**	0.689	0.654	0.635	0.625
MEAN	**0.74**	0.68	0.69	0.69	0.67

b)

Sound type	$L_{n,w}$	$L_{n,w} + C_I$	$L_{n,w} + C_{I,50}$	$L_{n,w} + C_{I,25}$	$L_{i,A,FMax,V,T}$
Rubber ball	**0.904**	0.867	0.863	0.896	0.852
Steel ball	0.818	0.765	0.777	0.717	**0.822**
Walking	0.778	0.754	0.763	**0.796**	0.678
Jumping	**0.726**	0.673	0.664	0.709	0.630
Chair	**0.807**	0.762	0.738	0.693	0.713
MEAN	**0.81**	0.76	0.76	0.76	0.74

band SPLs measured with Fast max weighting ($L_{iFavg,\ Fmax}$) explained well the annoyance ratings of rubber ball drops from 10 cm height on simulated wooden floors. After that, it would be more meaningful to assess how different alternative SNQs in different standards and literature explain the annoyance. Finally, it would be useful to derive an optimized SNQ that is associated with the annoyances of our experiment with highest possible correlation coefficient. An optimized SNQ for concrete floors has been published [25,26] and similar methodology could be applied for our experimental data.

It has been known for long (e.g. Ref. [27]), that the proportion of high frequency components produced by tapping machine is significantly higher than in walking. Walking can be safely assumed to be the most prevalent type of natural impact sounds although differences exist if residents use shoes or not. Jeon et al. [18] compared the three impact sources used in measurement standards (tapping machine, rubber ball, bang machine). The frequency characteristics of rubber ball was found to most resemble the spectrum of children jumping sounds in multi-storey residential buildings having concrete floors. Based on the psychoacoustic experiment of Ryu et al. [3], we expected that the SNQ obtained with the rubber ball ($L_{iA,Fmax,V,T}$) would explain annoyance better than the SNQs obtained with the tapping machine. Our results showed that the ISO standardized SNQ based on rubber ball dropping, $L_{iA,Fmax,V,T}$, explained mean *annoyance* of the five studied *sound types*, on average, worse than the four SNQs based on tapping machine. It was surprising that several SNQs based on tapping machine explained the mean *annoyance* of rubber ball better than $L_{iA,Fmax,V,T}$, which is based on the A-weighted rubble ball drops. Our finding agrees with Ref. [10]. They found that SNQs ($L_{n,w}$, $L_{nT,w} + C_I$, $L_{nT,w} + C_{I,50}$) based on the tapping machine explained annoyance caused by walking better than three SNQs based on the rubber ball drop. In their study, the three SNQs based on the tapping machine explained annoyance caused by rubber ball drop equally well than three SNQs based on the rubber ball drop. Therefore, based on our study, it is safe to use tapping machine as the primary impact sound source in the impact sound insulation measurements of wooden floors.

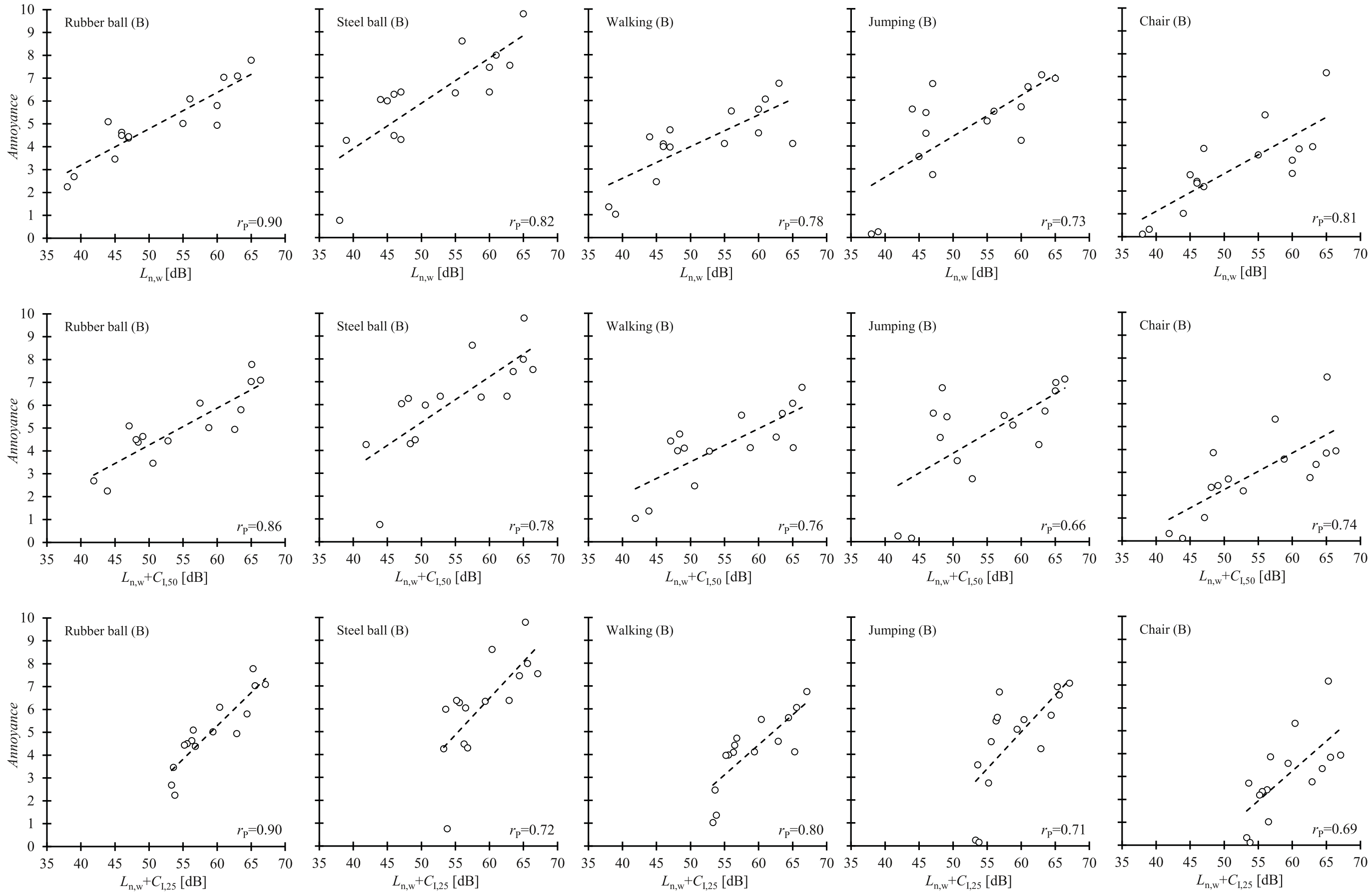

Fig. 8. Correlation between the single number values of 15 floors and mean *annoyance* rated by 52 participants in Experiment B. Top) $L_{n,w}$. Middle) $L_{n,w} + C_{I,50}$. Bottom) $L_{n,w} + C_{I,25}$.

4.2. Validity of the results in field

We used SNQs based on normalized impact SPL, L_n, obtained with a laboratory test. Laboratory test requires that flanking sound transmission is significantly suppressed. In field conditions, flanking transmission always exists, and the separating intermediate floor is not the only surface that transmits sound to the receiving room. Therefore, standardized impact SPL, L_{nT}, is used in many countries in field measurements. Standardized and normalized impact SPL are associated, both in laboratory and field conditions, by equation

$$L_n - L_{nT} = 10\cdot\log_{10}\left(\frac{V_2}{31.3}\right) \tag{2}$$

In this laboratory, L_n - L_{nT} = 3.1 dB. Because the constant is valid for all frequencies, the correlation coefficients obtained for SNQs based on $L_{n,w}$ are also valid for SNQs based on $L_{nT,w}$ or $L'_{nT,w}$.

4.3. Strengths and limitations

Our results were based on 15 wooden floors tested and recorded in the same laboratory. Two load-bearing slabs were involved: open-box timber slab and cross-laminated timber slab. Both suspended ceilings and floor coverings were varied on both slabs. We are not aware of prior experiments which covers such large number of wooden floors based on two different wooden load-bearing slabs.

The impact SPL of the 15 floors covers almost the whole range of impact SPL regulations applied in Europe. For example, the $L_{n,w}$ of studied floors ranged from 38 to 65 dB ($L_{nT,w}$ from 35 to 62 dB). For instance, the regulated values of $L'_{nT,w}$ in Europe range from 48 to 68 dB. On the other hand, Finland has the most stringent impact sound insulation regulations regarding low frequencies: it is mandatory to reach $L'_{nT,w} + C_{I,50} \leq 53$ dB between residential dwellings. Eight floors out of fifteen fulfilled this requirement ($L_{n,w}$ + $C_{I,50}$ range was 42–66 dB' $L'_{nT,w}$ + $C_{I,50}$ range was 39–63 dB). Therefore, our floors covered well also the most demanding sound insulation designs used in dwellings.

Room modes cause strong spatial variation of SPL in rooms especially below 200 Hz [12]. Since our natural impact sounds were expected to produce clearly audible components below 200 Hz (except Steel ball), we used two recording positions, A and B, in the receiving room. This way, we could implement two independent Experiments A and B, and we could also assess, whether the results are dependent on the choice of listening position in a modal field. This approach strengthened the methodological quality of our experiment. We are not aware of prior psychoacoustic studies in building acoustics where two fixed recording positions are used. The results suggest that the recording position plays a role in the perception. However, because the recording position was fixed within each Experiment, the comparison of the 75 sounds within both Experiments lead to almost similar outcome regarding the ranking order of SNQs. Based on that, it is not necessary to use more than one recording position in the future experiments. However, our results highlight the importance of doing the recordings for each floor in the same room position. This is only possible in laboratory conditions. In this light, such studies where the recordings for different floors are made in different rooms may contain large uncertainties caused by modal field (e.g., Ref. [8]).

We paid high attention to cover a broad range of sound frequencies present in natural impact sounds. Many natural impacts are produced by heavy and soft items, such as walking and jumping. On the other hand, residents often produce impacts on the floor by hard and light items (i.e., children's toys, vacuum cleaning, tool dropping). We deliberately did not use tapping machine in the psychoacoustic experiment to represent a high frequency impact sound since the sound of tapping machine is artificial and too "hasty" – it has no counterpart in real life. Therefore, we used periodic Steel ball drops as high-frequency impact sounds, and Rubber ball drop, Walking, and Jumping as low-frequency impact sounds. Chair pushing is somewhere between these extremes, and it represents a more continuous sound. Most previous psychoacoustic studies on wooden floors have focused on low-frequency natural sounds or even excluded high-frequency sounds. Therefore, our study provides a broader understanding on the perception of natural impact sounds on wooden floors.

Using the same laminate covering on every floor was a strength because we could produce comparable results between floor constructions also with Chair pushing, whose sound depends strongly on the microstructure and kinetic friction of the surface. Several prior studies have failed to produce reliable results with chair pushing because of varying floor covering (e.g., Refs. [4,8,13]).

The study was deliberately limited to wooden floors. It would be important to conduct a similar, highly controlled psychoacoustic experiment (using same *sound types*, laminate flooring, fixed recording laboratory) focusing only on concrete floors in a similar $L_{n,w}$ range to see how the five studied SNQs are associated with annoyance of natural impact sounds. This kind of work would enable the comparison of suitable SNQs between concrete and wooden floors and help the discussion whether different SNQs should be used depending on the building material of the slab.

ISI measurements using tapping machine and rubber ball are not described in ISO 10140-3 standard for 25–40 Hz [1]. We decided to follow the same measurement procedure as the standards describes for frequencies 50–5000 Hz. The accuracy of such measurements is unknown. The study of [5] suffers from the same limitation. For example, the uncertainty of reverberation time measurements increases towards low frequencies [24]. According to ISO 5725-1 [28], the generic accuracy of laboratory tests should be determined by accuracy experiments (a.k.a. inter-laboratory test, Round Robin test), where the same specimen, or preferably two specimens with small and large $L_{n,w}$ values, is tested in at least eight laboratories. The outcome of the analysis is the reproducibility standard deviation (SD), s_R, which is a superposition of within-laboratory SD (a.k.a. repeatability), s_L, and between-laboratory SD, s_L. The latter SD mostly determines the s_R value. We are not aware of accuracy experiments concerning ISI laboratory tests of floor constructions. Ref. [29] reports a Round Robin test where 20 independent laboratories (mainly consulting companies) measured the impact sound insulation of a floor in an office building according to ISO 16283-2 standard [30]. The standard deviations were 1.4 dB, 1.1 dB, and 1.0 dB for $L'_{nT,w}$, $L'_{nT,w} + C_I$, and $L'_{nT,w} + C_{I,50\text{-}2500}$, respectively. The frequency dependent SDs were quite similar within 50–1600 Hz. On top of that, Ref. [31] studied the standard deviation of SPLs in 40 ISI measurements conducted *in situ* according to ISO 16283-2. They found that the SDs between four measurement points were quite similar within 50–5000 Hz, and in most cases below 5 dB. The range 50–80 did not show especially large SDs. In general, the uncertainty within 50–80 Hz is a larger problem for airborne than for impact sound insulation measurements since the former requires SPL measurements also in the source room. In conclusion, there is an obvious need for an accuracy experiment concerning ISO 10140-3 within 20–5000 Hz so that the accuracy issues could be constructively discussed in the future.

We attempted to answer to the accuracy question related to ISO measurements and subjective ratings by using the same floor construction twice. Floors O1 and O2 were identical but their recordings and ISI measurements were based on independent installations (see **Sec. 2.3**). Based on Table 1, the objective differences between O1 and O2 were 2.0, 0.8, 1.4, 1.5 and 1.6 dB for $L_{n,w}$, $L_{n,w} + C_I$, $L_{n,w} + C_{I,50}$, $L_{n,w} + C_{I,25}$, and $L_{iA,Fmax,V,T}$, respectively. Installation O2 had somewhat higher values than O1. The differences of three first SNQs agree with the SDs reported by Ref. [29]. Based on Table 2, the A-weighted equivalent SPLs (L_{Aeq}) of the natural impact sounds (*sound types*) measured in positions A and B differed at most 3.3 dB between floors O1 and O2. Also here, O2 was louder. Considering that single-number values were higher for O2, and natural impact sound recordings are not spatially averaged and inevitably involve larger SD than the SNQs do, the obtained differences in

L_{Aeq} were acceptably low. The evaluation suggests that our floor installations, ISI tests, and natural impact sound stimuli were sufficiently repeatable. Based on Fig. 7, the mean *annoyance* ratings differed between O2 and O1 by −0.12… +0.58 in Experiment A and by −0.44… +0.69 in Experiment B, depending on *sound type*. On average, the mean *annoyance* ratings were 0.27 and 0.18 units higher for floor O2 than for floor O1 in Experiment A and B, respectively. This difference agrees with the objective findings.

Our experiment suffers from the generic limitation concerning all psychophysical experiments: the results can depend on the number and choices of the stimuli (floor types, distribution of the single-number values between floors, impact sound types). It would be beneficial to have larger number of stimuli to obtain more reliable results. However, our experiment was very long. To avoid fatigue, we decided to limit the number of stimuli to 75 and repeat the stimuli obtained in two recording positions. In human factor research, a single experiment can never be used to propose strong conclusions, even if it would be excessively broad. Therefore, further independent experiments are needed before stronger conclusions can be made.

5. Conclusions

Our study represents one of the first major psychoacoustic experiments which has investigated how well the standardized single-number quantities of impact sound insulation are associated with the subjective annoyance produced by natural impact sounds on wooden floors. The study involved large number of participants, large range of wooden floor constructions, five spectrally different natural impact sound types, and assessment of each stimulus based on two recording positions under the floor. Because the stimulus heard by the participants was precisely controlled, our study provides a significant contribution in this field of science.

Our results suggest that perceived annoyance of impact sounds was best associated with $L_{\mathrm{n,w}}$ (based on 100−3150 Hz) for all the five natural sound types. The finding suggests that measurements in the range 50–80 Hz are not necessary for wooden floors as $L_{\mathrm{n,w}} + C_{\mathrm{I,50}}$ and $L_{\mathrm{iA,Fmax,V,T}}$ requires. Furthermore, it was neither justified to measure frequencies 25−40 Hz as $L_{\mathrm{n,w}} + C_{\mathrm{I,25}}$ requires.

Our experiment showed that all four SNQs based on tapping machine explained annoyance better than the SNQ based on rubber ball for wooden floors. This was true even for the *sound type* rubber ball, where we expected an opposite result. Based on this experiment, prioritizing rubber ball over tapping machine in wooden floor measurements is not justified.

Our study involved two Experiments A and B, because we had two recording positions, A and B, under the floor. Although the SPLs in positions A and B were slightly different, both experiments led to quite similar ranking order of SNQs. Therefore, it seems to be sufficient to use only one recording position in future experiments. However, it is extremely important, due to room modes, to apply a fixed recording room and a fixed recording position for every floor to avoid the confounding effect of room modes on SPL.

Because strong evidence in psychological research must be based on several independent experimental studies pointing in the same direction, more research is needed in this field before strong conclusions can be made.

CRediT authorship contribution statement

Valtteri Hongisto: Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization, Writing - original draft, Writing - review & editing. **Johann Laukka:** Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Reijo Alakoivu:** Validation, Investigation. **Juho Virtanen:** Visualization, Resources, Investigation. **Jarkko Hakala:** Visualization, Resources, Investigation. **Andreas Linderholt:** Writing – original draft, Funding acquisition, Conceptualization. **Kirsi Jarnerö:** Project administration, Funding acquisition. **Jörgen Olsson:** Writing – original draft, Project administration. **Jukka Keränen:** Writing – original draft, Methodology, Investigation.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2023.110727.

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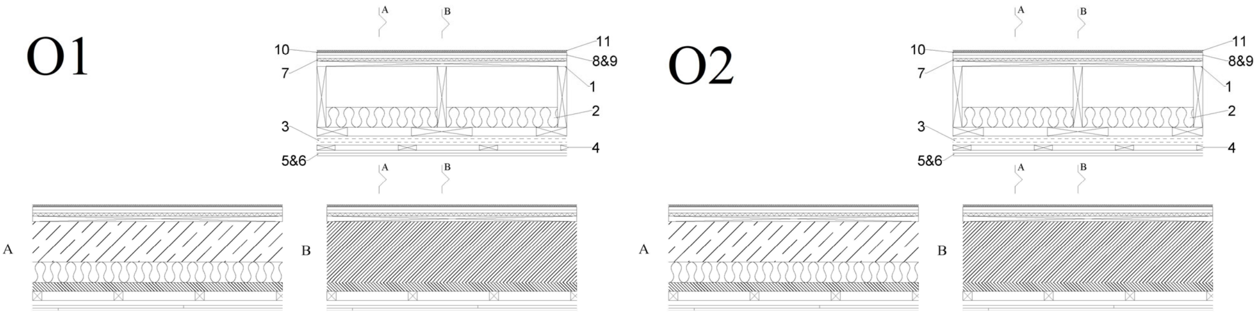
SUPPLEMENTARY MATERIAL

Title: Suitability of standardized single-number ratings of impact sound insulation for wooden floors – Psychoacoustic experiment

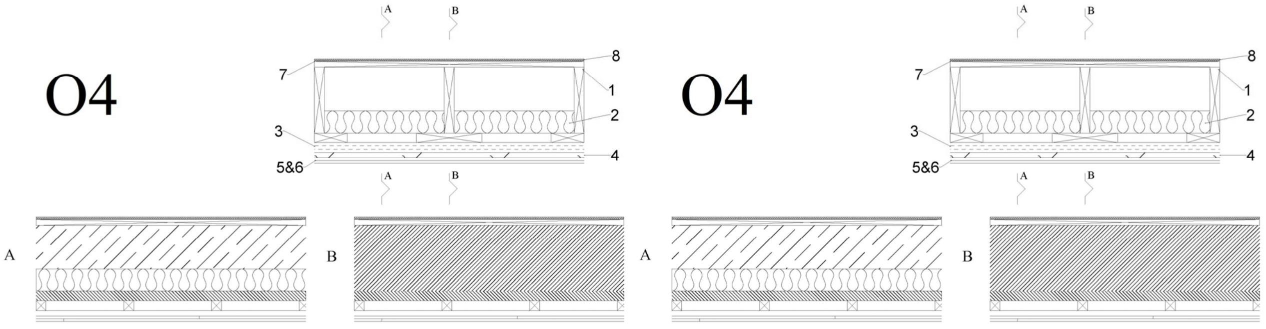
Authors: Valtteri Hongisto, Johann Laukka, Reijo Alakoivu, Juho Virtanen, Jarkko Hakala, Andreas Linderholt, Kirsi Jarnerö, Jörgen Olsson, Jukka Keränen

Updated 25th August, 2023



1. Open box slab 370 mm
2. 100 mm glass wool, 10 kg/m3
3. 45 mm timber stud, 45x45 mm, cc 400 mm
4. 25 mm timber stud, 25x100 mm, cc 400 mm
5. 13 mm gypsum board, 8.4 kg/m2 (screwing cc 200 mm ends cc 300 mm sides)
6. 13 mm gypsum board, 8.4 kg/m2 (screwing cc 200 mm ends cc 300 mm sides)
7. 13 mm glass wool, 24 MN/m3, 1.5 kg/m2
8. 15 mm gypsum board, 15.4 kg/m2
9. 15 mm gypsum board, 15.4 kg/m2
10. 3.0 mm EPS underlayment, 0.14 kg/m2, 64 MN/m3
11. 8 mm laminate, 7.3 kg/m2

1. Open box slab 370 mm
2. 100 mm glass wool, 10 kg/m3
3. 45 mm timber stud, 45x45 mm, cc 400 mm
4. 25 mm timber stud, 25x100 mm, cc 400 mm
5. 13 mm gypsum board, 8.4 kg/m2 (screwing cc 200 mm ends cc 300 mm sides)
6. 13 mm gypsum board, 8.4 kg/m2 (screwing cc 200 mm ends cc 300 mm sides)
7. 13 mm glass wool, 24 MN/m3, 1.5 kg/m2
8. 15 mm gypsum board, 15.4 kg/m2
9. 15 mm gypsum board, 15.4 kg/m2
10. 3.0 mm EPS underlayment, 0.14 kg/m2, 64 MN/m3
11. 8 mm laminate, 7.3 kg/m2



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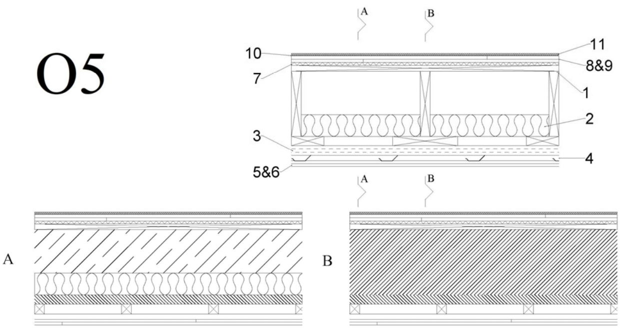
2. 100 mm glass wool, 10 kg/m3
3. 45 mm timber stud, 45x45 mm, cc 400 mm
4. 25 mm resilient stud, 0.32 MN/m2, cc 400 mm
5. 13 mm gypsum board, 8.4 kg/m2 (screwing cc 200 mm ends cc 300 mm sides)
6. 13 mm gypsum board, 8.4 kg/m2 (screwing cc 200 mm ends cc 300 mm sides)
7. 3.0 mm EPS underlayment, 0.14 kg/m2, 64 MN/m3
8. 8 mm laminate, 7.3 kg/m2

1. Open box slab 370 mm
2. 100 mm glass wool, 10 kg/m3
3. 45 mm timber stud, 45x45 mm, cc 400 mm
4. 25 mm resilient stud, 0.32 MN/m2, cc 400 mm
5. 13 mm gypsum board, 8.4 kg/m2 (screwing cc 200 mm ends cc 300 mm sides)
6. 13 mm gypsum board, 8.4 kg/m2 (screwing cc 200 mm ends cc 300 mm sides)
7. 3.0 mm EPS underlayment, 0.14 kg/m2, 64 MN/m3
8. 8 mm laminate, 7.3 kg/m2

Fig. S1. Structure drawings of floors O1–O4 based on the open box timber slab. It should be noted that floors O1 and O2 have the same construction, but they have been measured for several months apart (re-building in between). The drawings are shown with better resolution in **Ref. [17]**.

O5



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4. 25 mm resilient stud, 0.32 MN/m2, cc 400 mm
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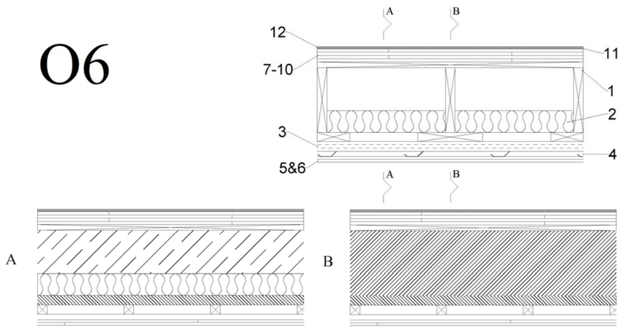
6. 13 mm gypsum board, 8.4 kg/m2 (screwing cc 200 mm ends cc 300 mm sides)
7. 13 mm glass wool, 24 MN/m3, 1.5 kg/m2
8. 15 mm gypsum board, 15.4 kg/m2
9. 15 mm gypsum board, 15.4 kg/m2
10. 3.0 mm EPS underlayment, 0.14 kg/m2, 64 MN/m3
11. 8 mm laminate, 7.3 kg/m2

O6



1. Open box slab 370 mm
2. 100 mm glass wool, 10 kg/m3
3. 45 mm timber stud, 45x45 mm, cc 400 mm
4. 25 mm resilient stud, 0.32 MN/m2, cc 400 mm
5. 13 mm gypsum board, 8.4 kg/m2 (screwing cc 200 mm ends cc 300 mm sides)
6. 13 mm gypsum board, 8.4 kg/m2 (screwing cc 200 mm ends cc 300 mm sides)
7. 15 mm gypsum board, 15.4 kg/m2
8. 15 mm gypsum board, 15.4 kg/m2
9. 15 mm gypsum board, 15.4 kg/m2
10. 15 mm gypsum board, 15.4 kg/m2
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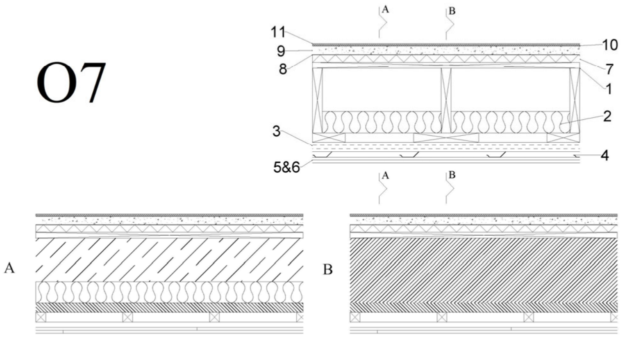
12. 8 mm laminate, 7.3 kg/m2

O7



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2. 100 mm glass wool, 10 kg/m3
3. 45 mm timber stud, 45x45 mm, cc 400 mm
4. 25 mm resilient stud, 0.32 MN/m2, cc 400 mm
5. 13 mm gypsum board, 8.4 kg/m2 (screwing cc 200 mm ends cc 300 mm sides)
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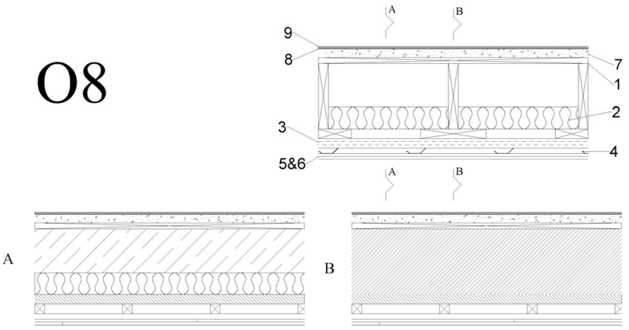
8. Geotextile
9. 40 mm floor screed, 68 kg/m2
10. 3.0 mm EPS underlayment, 0.14 kg/m2, 64 MN/m3
11. 8 mm laminate, 7.3 kg/m2

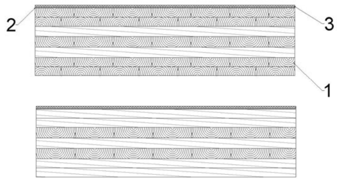
O8



1. Open box slab 370 mm
2. 100 mm glass wool, 10 kg/m3
3. 45 mm timber stud, 45x45 mm, cc 400 mm
4. 25 mm resilient stud, 0.32 MN/m2, cc 400 mm
5. 13 mm gypsum board, 8.4 kg/m2 (screwing cc 200 mm ends cc 300 mm sides)
6. 13 mm gypsum board, 8.4 kg/m2 (screwing cc 200 mm ends cc 300 mm sides)
7. 40 mm floor screed, 68 kg/m2
8. 3.0 mm EPS underlayment, 0.14 kg/m2, 64 MN/m3
9. 8 mm laminate, 7.3 kg/m2

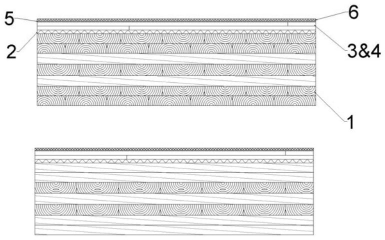
Fig. S2. Structure drawings of floors O5−O8 based on the open box timber slab. The drawings are shown with better resolution in **Ref. [17]**.

C1



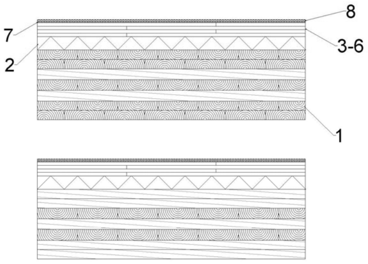
1. Cross-laminated timber slab 260 mm (edge-glued)
2. 3.0 mm EPS underlayment, 0.14 kg/m2, 64 MN/m3
3. 8 mm laminate, 7.3 kg/m2

C2



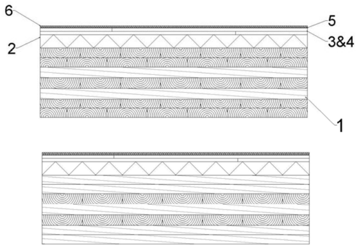
1. Cross-laminated timber slab 260 mm (edge-glued)
2. 13 mm glass wool, 24 MN/m3, 1.5 kg/m2
3. 15 mm gypsum board, 15.4 kg/m2
4. 15 mm gypsum board, 15.4 kg/m2
5. 3.0 mm EPS underlayment, 0.14 kg/m2, 64 MN/m3
6. 8 mm laminate, 7.3 kg/m2

C3



1. Cross-laminated timber slab 260 mm (edge-glued)
2. 50 mm glass wool, 8 MN/m3, 3.4 kg/m2
3. 15 mm gypsum board, 15.4 kg/m2
4. 15 mm gypsum board, 15.4 kg/m2
5. 15 mm gypsum board, 15.4 kg/m2
6. 15 mm gypsum board, 15.4 kg/m2
7. 3.0 mm EPS underlayment, 0.14 kg/m2, 64 MN/m3
8. 8 mm laminate, 7.3 kg/m2

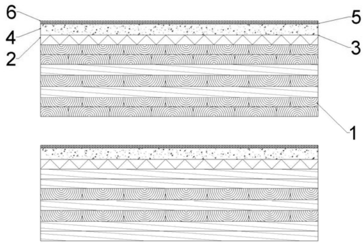
C4



1. Cross-laminated timber slab 260 mm (edge-glued)
2. 50 mm glass wool, 8 MN/m3, 3.4 kg/m2
3. 15 mm gypsum board, 15.4 kg/m2
4. 15 mm gypsum board, 15.4 kg/m2
5. 3.0 mm EPS underlayment, 0.14 kg/m2, 64 MN/m3
6. 8 mm laminate, 7.3 kg/m2

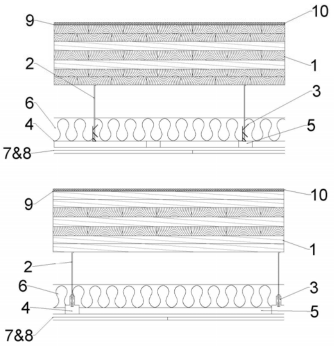
Fig. S3. Structure drawings of floors C1−C4 based on the cross-laminated timber slab. The drawings are shown with better resolution in **Ref. [17]**.

C5



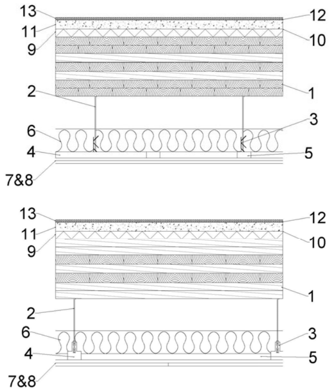
1. Cross-laminated timber slab 260 mm (edge-glued)
2. 35 mm EPS, 12 MN/m3
3. Geotextile
4. 40 mm floor screed, 68 kg/m2
5. 3.0 mm EPS underlayment, 0.14 kg/m2, 64 MN/m3
6. 8 mm laminate, 7.3 kg/m2

C6



1. Cross-laminated timber slab 260 mm (edge-glued)
2. Hanging wire (steel 4 mm)
3. Adjustable hanger (steel 0.8 mm) 0,83 pcs/m2
4. Longitudinal support (steel stud) cc 800 mm
5. Transverse support (steel stud) cc 400 mm
6. 100 mm glass wool 10 kg/m3
7. 13 mm gypsum board 8.4 kg/m2 (screwing cc 200 mm ends & sides, cc 300 mm middle)
8. 13 mm gypsum board 8.4 kg/m2 (screwing cc 200 mm ends & sides, cc 300 mm middle)
9. 3.0 mm EPS underlayment, 0.14 kg/m2, 64 MN/m3
10. 8 mm laminate, 7.3 kg/m2

C7



1. Cross-laminated timber slab 260 mm (edge-glued)
2. Hanging wire (steel 4 mm)
3. Adjustable hanger (steel 0.8 mm) 0,83 pcs/m2
4. Longitudinal support (steel stud) cc 800 mm
5. Transverse support (steel stud) cc 400 mm
6. 100 mm glass wool 10 kg/m3
7. 13 mm gypsum board 8.4 kg/m2 (screwing cc 200 mm ends & sides, cc 300 mm middle)
8. 13 mm gypsum board 8.4 kg/m2 (screwing cc 200 mm ends & sides, cc 300 mm middle)
9. 35 mm EPS 12 MN/m3
10. Geotextile
11. 40 mm floor screed 68 kg/m2
12. 3.0 mm EPS underlayment 0.14 kg/m2 64 MN/m3
13. 8 mm laminate 7.3 kg/m2

Fig. S4. Structure drawings of floors C5−C7 based on the cross-laminated timber slab. The drawings are shown with better resolution in **Ref. [17]**.

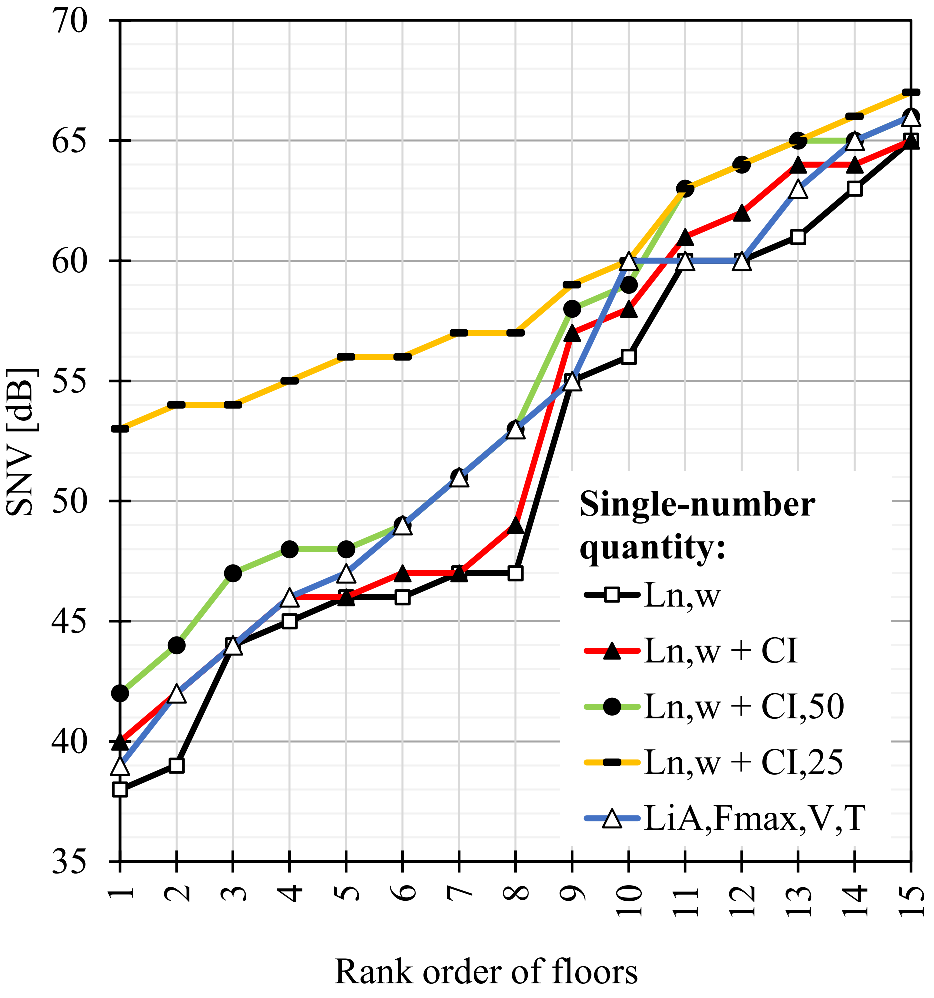


Fig. S5. Distribution of the single-number values, SNV, among the 15 rank-ordered floors. The figure is a reorganization of the data shown in **Table 1**. The distribution of the SNVs is good since there are only 2 or 3 floors among each SNQ having the same SNV.

Fig. S6. Typical variation of the A-weighted SPL between successive walkthroughs. The example concerns *floor type* C2.

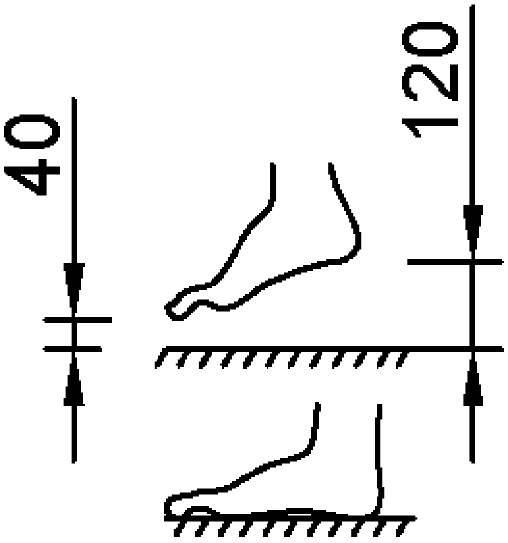


Fig. S7. Trajectory of metatarsus in the extreme positions of Jumping. It should be noted that the heel did not strongly hit the floor despite of the touch. The strongest impact was caused by the hit of the ball.

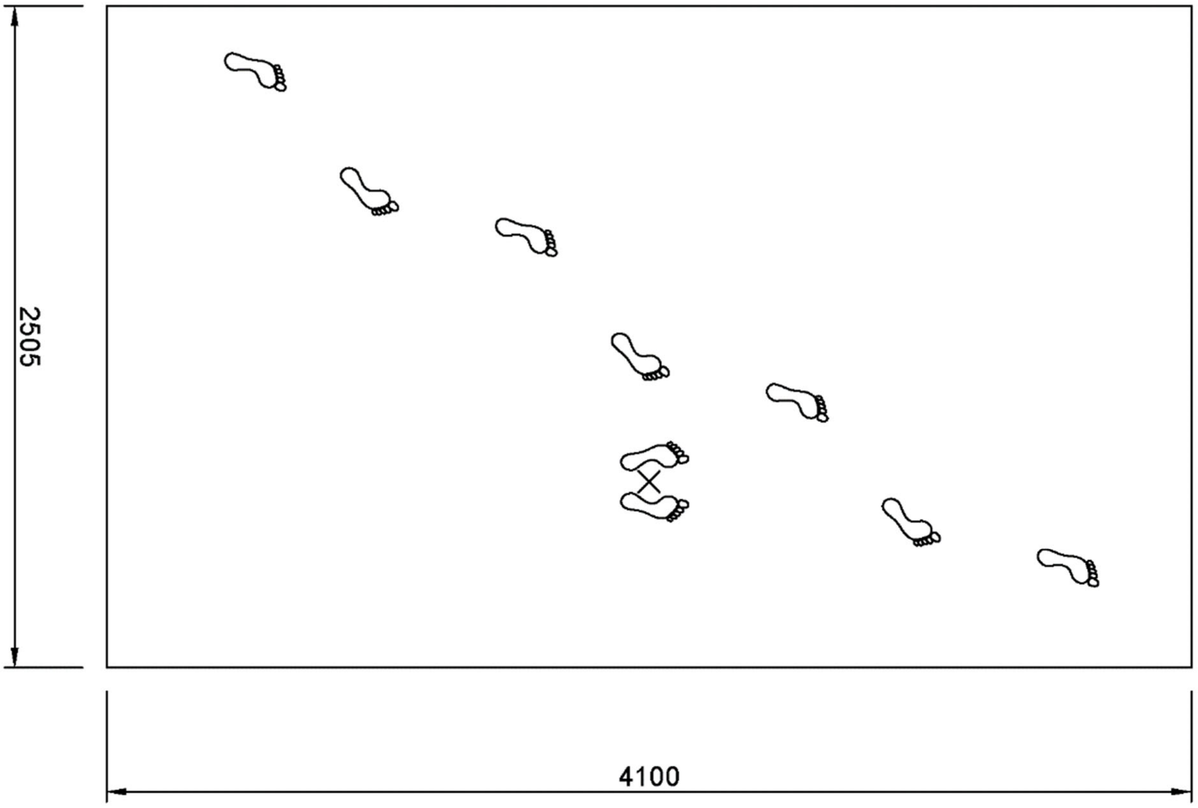
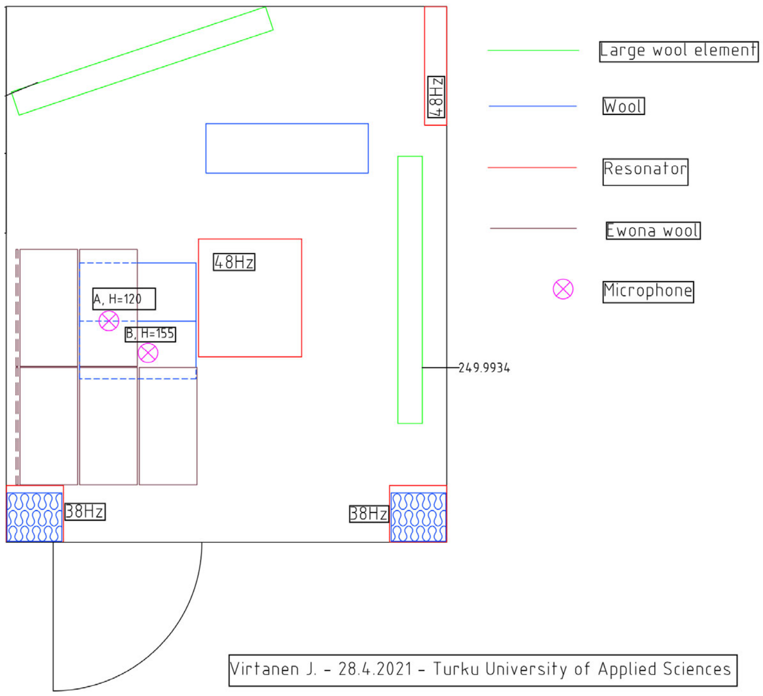


Fig. S8. Positions of the natural impact stimuli on the wooden floor. The Walking path and Jumping position are shown with footprints. The cross indicates the dropping position of Rubber ball and Steel ball. Chair pushing followed the same diagonal as Walking.



- 13 pieces of $1200mm \times 590mm \times 20mm$ wool boards hanging from the ceiling, with air cavity of 100 mm behind
- Two $2740mm \times 1780mm \times 250mm$ vertical wool elements on the floor. One had a 280 mm distance to the wall (aligned with wall). Another had 0–840 mm distance to the wall (inclined to the wall).
- Two cubic Helmholz resonators (38 Hz) in opposite floor corners of the room.
- Two panel resonators (48 Hz). One in the room corner, another in the middle of the floor.
- Two bales of glass wool 0,39 m^3 each. One of the bales is placed on top of a Helmholz resonator. Another on top of the fixed loudspeaker of the room.
- Three $1660mm \times 510mm \times 28mm$ boards of wool on top of each other, lying on the floor.
- Two $1190mm \times 595mm \times 50mm$ boards of wool lying on the floor, under the recording microphones A and B.

Fig. S9. Placement of the absorbers in the impact sound insulation laboratory during the recording of natural impact sounds.

Fig. S10. Placement of the absorbers in the impact sound insulation laboratory during the recording of natural impact sounds. The loudspeaker shown in three figures was not present during the recordings. The positions of the recording microphones are also shown.

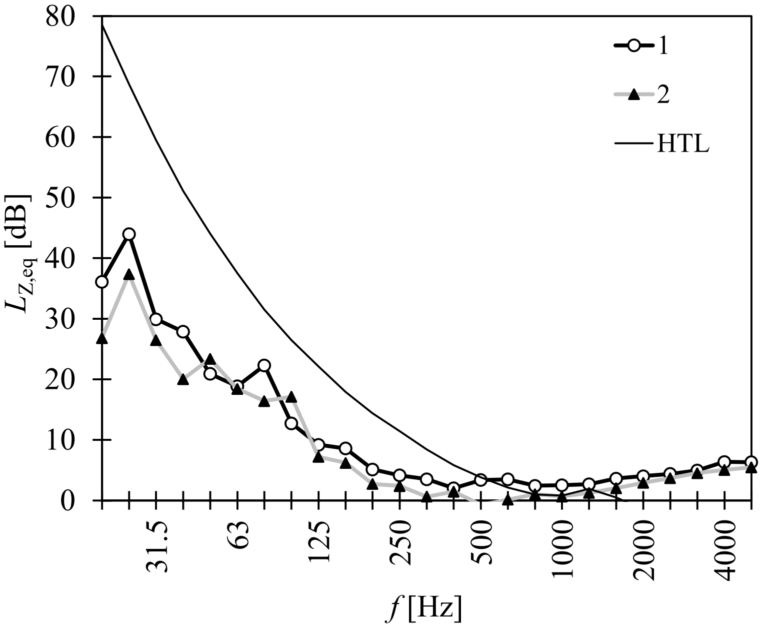


Fig. S11. Unweighted equivalent SPL, $L_{Z,eq}$, of background noise in impact sound insulation laboratory during the recording of impact sounds (1) and in the psychophysics laboratory (2). Both rooms were unoccupied during the measurement. The corresponding A-weighted total SPLs are 15.7 and 14.3 dB L_{Aeq}, respectively. Electric background noise from the microphone is causing the positive SPLs above 400 Hz. The hearing threshold level (HTL) according to ISO 226 is also indicated.

Fig. S12. A photograph of the psychophysics laboratory, where the psychoacoustic experiment was conducted. Here, the head-and-torso simulator is placed in the position of participant. The head-and-torso simulator was used to measure that the 75 experimental sounds are played at the same sound pressure level as recorded in the impact sound insulation laboratory.

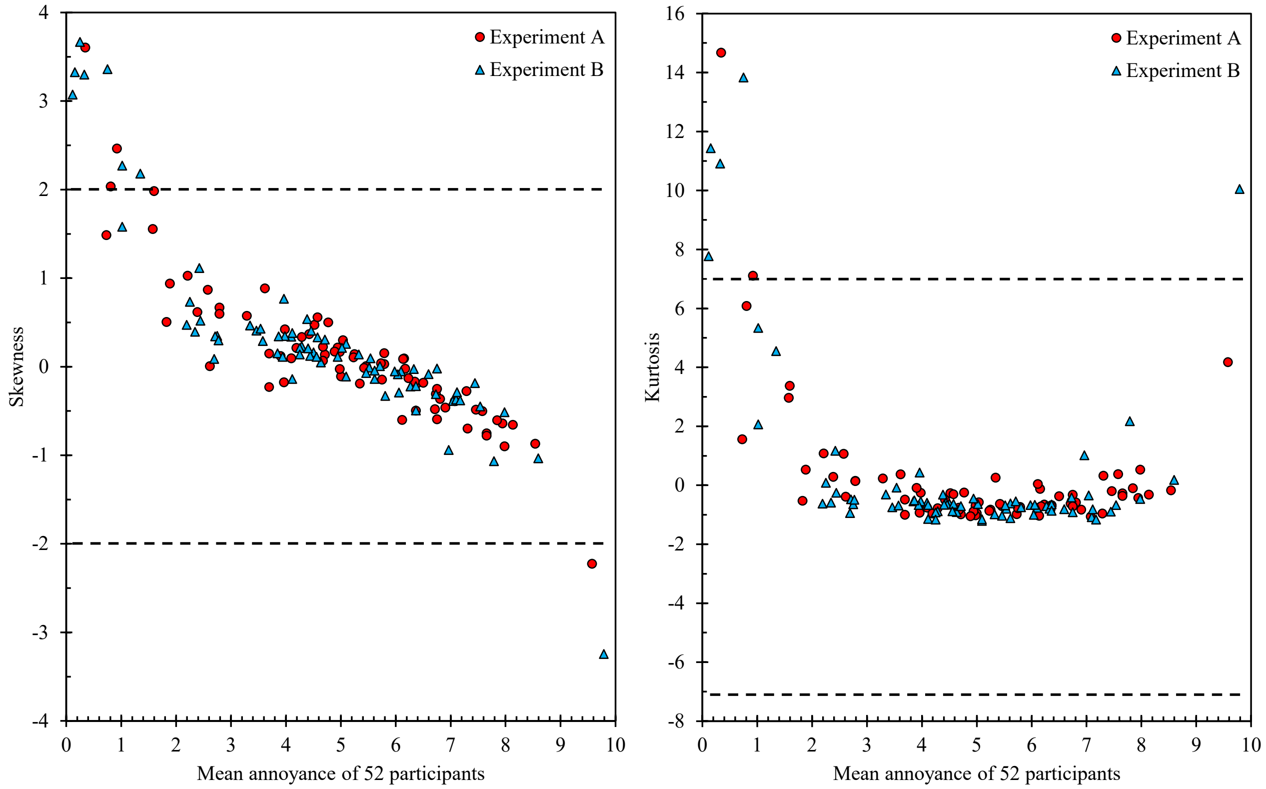


Fig. S13. The assessment of the normal distribution of 52 *annoyance* responses in Experiments A and B. If Skewness is within -2 and +2 and Kurtosis is within -7 and +7, the distribution is normal and mean value represents the data very well. The abovementioned limits are indicated with horizontal dashed lines. Violation of these criteria occurred for a few extreme annoyance ratings.

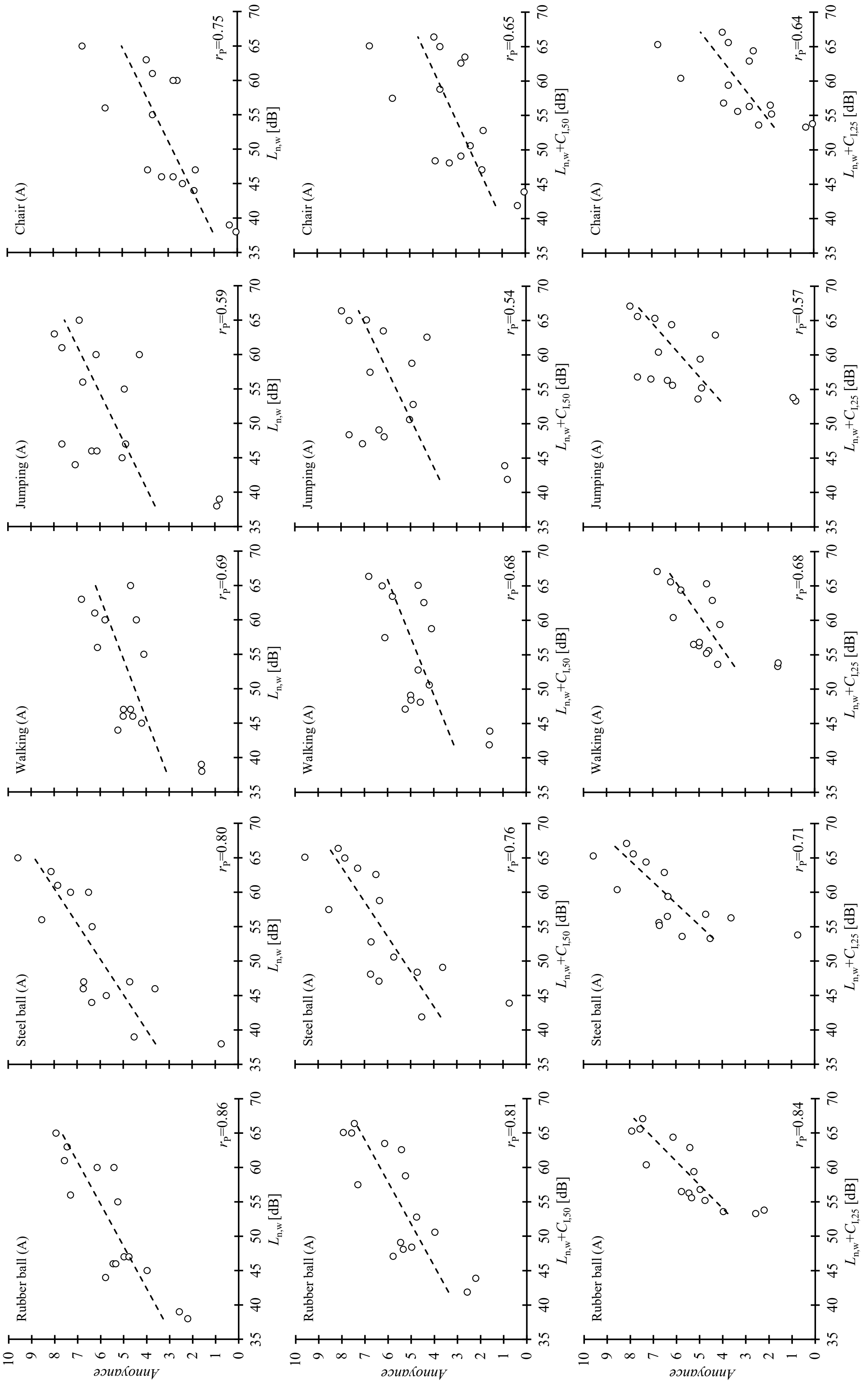


Fig. S14. Correlation between the single number values of 15 floor types and mean *annoyance* rated by 52 participants in Experiment A. Left) $L_{n,w}$. Middle) $L_{n,w}$ +$C_{I,50}$. Right) $L_{n,w}$ +$C_{I,25}$.

Table S1. Normalized impact sound pressure level, L_n, as a function of frequency, f, for 15 studied floors. Measurements were conducted according to ISO 10140-3 using the tapping machine.

f [Hz]	L_n [dB]														
	O1	O2	O3	O4	O5	O6	O7	O8	C1	C2	C3	C4	C5	C6	C7
25	65.1	65.3	59.3	69.7	64.1	63.9	65.2	65.5	65.3	61.9	57.4	62.8	64.7	65.9	67.3
32	66.2	65.6	71.2	66.0	67.1	65.2	66.7	64.4	60.1	59.5	63.7	62.1	59.0	63.8	61.3
40	69.3	72.8	64.8	65.1	65.0	68.2	67.0	65.1	61.2	60.0	58.3	59.8	59.9	47.8	49.2
50	64.4	64.2	57.9	58.9	56.7	55.4	53.9	52.9	54.0	52.9	58.4	56.9	53.0	46.1	42.9
63	69.6	69.2	66.3	58.1	55.6	54.8	51.6	51.9	57.1	58.6	60.2	62.9	61.0	49.5	54.1
80	72.6	76.1	73.5	63.1	53.0	51.9	51.4	56.1	60.3	66.1	57.7	61.1	61.6	47.9	47.0
100	72.6	73.5	69.4	67.4	57.0	51.9	56.4	53.6	65.2	70.3	56.6	60.3	74.2	48.9	52.1
125	74.8	75.0	70.9	65.9	56.7	51.4	57.2	52.9	63.7	67.5	54.7	56.6	73.1	46.2	53.9
160	72.4	73.5	71.7	61.2	54.8	51.6	51.7	51.8	69.4	58.9	50.9	54.2	63.9	47.3	41.4
200	64.2	67.3	63.9	59.2	51.1	51.0	50.4	50.7	70.8	60.1	53.6	55.6	65.1	47.8	44.6
250	59.8	63.6	64.2	61.5	48.4	50.9	53.7	52.7	73.9	55.5	49.1	49.8	59.5	46.0	33.0
315	57.3	61.4	62.2	59.7	46.5	49.1	51.3	54.1	72.9	54.2	48.1	47.5	59.7	41.6	27.5
400	53.1	57.1	58.1	56.3	43.1	46.9	49.2	50.3	72.2	50.0	45.6	44.3	55.3	38.2	21.5
500	42.7	47.1	48.5	49.8	31.6	40.7	40.9	44.0	69.0	43.8	40.3	39.9	48.8	36.0	15.3
630	34.3	35.0	36.1	43.9	26.4	34.4	28.6	38.1	65.0	38.8	32.7	34.3	40.1	33.8	9.5
800	29.1	30.0	26.6	42.8	22.4	32.0	21.6	34.6	61.3	32.5	28.0	28.2	31.8	29.8	6.1
1000	24.2	24.6	20.2	40.8	15.8	25.0	13.3	31.3	57.1	26.4	24.9	25.7	27.4	25.6	4.8
1250	20.7	20.4	12.8	38.2	11.3	20.1	6.1	24.1	51.5	24.9	20.7	22.7	20.2	20.0	-0.6
1600	13.3	14.7	4.6	36.9	5.7	15.9	1.1	17.4	45.5	21.7	17.4	18.8	16.1	11.9	-1.4
2000	5.8	7.0	0.7	34.0	1.9	9.1	0.1	9.4	42.0	18.4	13.1	15.0	13.2	10.8	-0.9
2500	3.6	3.0	1.9	33.3	1.1	3.7	1.9	4.2	41.5	17.6	11.2	13.1	13.0	14.8	0.0
3150	2.7	2.9	3.2	31.3	2.1	2.6	3.3	3.1	39.6	12.0	9.6	10.6	12.5	8.5	1.6
4000	3.2	3.9	3.4	22.1	3.5	3.2	3.6	3.0	36.5	6.5	6.4	6.9	8.4	5.6	3.4
5000	4.9	5.6	5.4	12.9	4.8	4.2	4.8	4.0	33.2	5.8	6.6	6.8	6.5	5.2	4.9

Table S2. Standardized maximum impact sound pressure level, $L_{i,Fmax,V,T}$, as a function of frequency, f, for 15 studied floors. Measurements were conducted according to ISO 10140-3 using the heavy/soft impact source, i.e., rubber ball drops from 1.00 m height.

f [Hz]	$L_{i,Fmax,V,T}$ [dB]														
	O1	O2	O3	O4	O5	O6	O7	O8	C1	C2	C3	C4	C5	C6	C7
25	83.4	84.0	80.4	86.9	84.8	82.6	82.3	82.6	82.0	80.0	77.0	79.8	80.4	84.9	84.4
32	90.3	90.8	93.5	87.0	89.2	86.5	87.4	85.5	80.9	82.7	84.6	83.7	81.3	84.1	82.9
40	88.4	89.9	83.7	84.3	87.0	85.5	81.9	84.9	80.1	81.2	76.5	80.2	78.6	70.2	70.8
50	78.7	79.6	74.2	76.7	73.7	71.8	66.8	71.9	71.3	70.0	76.1	74.2	67.5	66.9	60.7
63	72.1	72.4	70.0	67.3	62.2	59.8	56.1	57.8	62.6	63.6	69.2	70.5	62.1	57.5	56.2
80	77.9	78.5	74.2	63.1	57.8	50.4	52.6	51.9	63.2	70.9	65.7	72.3	64.2	50.8	49.4
100	73.3	72.3	67.2	58.5	56.6	50.0	50.4	49.3	63.7	73.6	59.5	66.6	71.9	45.3	49.1
125	77.2	74.0	69.9	58.6	58.5	50.0	51.5	49.1	62.8	70.4	54.0	58.2	72.7	43.4	51.1
160	72.2	68.7	67.3	54.4	54.2	48.4	43.8	43.8	66.8	62.0	50.8	55.2	62.4	43.8	40.2
200	60.8	63.6	58.1	50.7	47.7	47.7	43.1	41.1	70.0	63.1	54.5	60.1	62.2	47.5	38.2
250	52.3	56.2	54.5	48.5	42.1	46.5	45.1	42.5	64.3	48.2	43.5	45.3	51.2	37.8	25.4
315	49.6	54.4	54.6	49.1	41.3	45.7	41.9	45.5	64.7	46.2	42.0	43.7	50.5	33.3	22.1
400	47.0	49.3	50.0	48.1	38.1	43.8	39.9	42.9	64.4	43.4	40.7	40.3	46.4	31.4	21.6
500	40.9	42.5	40.5	42.0	33.8	38.5	29.5	35.6	61.8	37.5	37.7	36.5	38.6	27.8	19.6
630	37.6	38.1	35.1	40.2	32.8	34.1	24.6	34.7	59.3	33.4	31.4	34.9	31.0	25.5	17.6
800	36.6	35.7	31.0	38.2	32.2	32.9	22.0	31.2	54.9	28.1	27.9	34.4	25.0	26.3	16.6
1000	33.9	33.3	27.8	35.7	27.2	28.0	17.1	26.9	49.1	25.5	26.1	33.8	20.3	19.3	11.3
1250	32.3	31.6	25.7	31.0	24.6	22.7	15.6	23.7	43.2	21.9	23.0	32.0	11.8	16.4	14.3
1600	30.0	30.5	25.0	28.1	25.1	21.5	14.0	22.8	36.1	18.2	18.5	30.6	8.7	12.0	9.0
2000	28.2	27.8	22.4	27.4	22.1	18.9	12.3	22.2	34.1	15.8	16.4	30.5	8.0	10.1	6.3
2500	29.7	29.4	23.9	29.4	22.4	19.3	12.5	25.1	32.6	15.0	18.7	26.8	8.7	11.5	5.7
3150	30.5	30.1	24.3	30.3	21.7	17.9	11.8	27.1	30.5	14.3	19.3	22.7	8.0	9.8	5.1
4000	27.0	26.8	21.6	26.9	17.6	13.1	10.5	24.5	28.2	13.2	17.1	20.0	6.0	6.4	4.8
5000	24.1	23.9	17.7	24.1	15.7	10.5	8.8	22.3	26.4	11.3	13.3	16.9	4.9	5.3	4.7