A laboratory listening experiment on subjective and objective rating of impact sound insulation of concrete floors

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ABSTRACT

A listening experiment on the associations between single-number quantities (SNQs) of impact sound insulation and subjective rating of impact sounds was conducted. The experiment was participated by 55 subjects in order to rate subjectively 44 sounds which were recordings of five actual impact sound sources directed to nine floor types. Eight objective SNQs were calculated for the floor types. A correlation analysis between the objective SNQs and subjective annoyance or loudness was carried out. The best standardized indicators of subjective loudness regarding walking with hard-heeled and soft-heeled shoes and chair moving were $L'_{n,w} + C_I$, $L'_{n,w} + C_{I,50\text{-}2500}$. As well correlating indicators were also the SNQs developed by Fasold, Gerretsen and Bodlund. The indicators $L'_{n,w}$ and the SNQ developed by Hagberg correlated less with the subjective loudness and annoyance of the mentioned three sound types. The subjective ratings of walking with socks and superball bouncing were weakly correlated with the SNQs. Thus, there is a need for the development of new SNQs which would correlate better with general sound types.

Keywords: impact sound insulation, psychoacoustics, subjective assessment, annoyance
I-INCE Classification of Subjects Numbers: 51.3, 63.2

1. INTRODUCTION

It has been long recognized that impact sound insulation should be expressed by such single-number quantities (SNQ) which are as well as possible associated with people's experience on impact sounds, such as walking. It is also obvious that a standardized sound source able to generate repeatable excitation is needed (1, 2). Therefore, the formulation of a SNQ for impact sound insulation requires physical measurements of impact sound levels generated by the sound sources and psychoacoustic listening experiments concerning walking and other usual impact sounds.

On the basis of the recent listening experiments it is possible to conclude that the SNQs which were developed for rating of heavy concrete floors in the 1950s are not necessarily applicable to rating of lightweight floors (3–7). As Späh et al (7) state, an adequate SNQ for rating of impact sound insulation should comprise all floor constructions, lightweight as well as massive floors. At the moment, a great majority of European dwellings are constructed of concrete or other massive structures (8). There is earlier research referring to importance of low-frequency sound in the case of certain heavy-weight floors (9–11). A recent study dealing with concrete floors (12) showed that walking with socks generates sound pressure levels which at frequency bands below 100 Hz are higher than the sound pressure levels generated by walking with hard-heeled or soft-heeled shoes. The results also confirmed that compared with walking on other floor coverings on load-bearing concrete slab, walking on floating floors may generate 5–15 dB higher sound pressure levels below 100 Hz. The meaning of thos kind of sounds regarding subjective annoyance in buildings can be verified only with psychoacoustic experiments.

A reliable correlation analysis on the basis of listening test requires quite a large amount of data. In many of the recent listening experiments, the number of the subjects has been rather small, around 20 persons or less (3–7). The risk of coincidence and resulting wrong conclusions increases with decreasing number of subjects.

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The purpose of this study was to determine the associations between subjective ratings of impact sounds and various standardized and alternative single-number quantities of impact sound insulation. The focus was on concrete floors with various kinds of floor coverings. The present standardized single-number quantities expect that the main impact source is walking with hard-heeled shoes. This sound type does not necessarily reflect the most typical impact sounds in all countries (12, 13). Special care was taken that large number of subjects was used to guarantee strong statistical power, large range of impact sound insulation levels were involved, and that various kinds of realistic impact sounds were used in order to reflect the real situation in residential dwellings. Our study focused on frequency range 50–5000 Hz. Light-weight constructions were not included to our study. The methods and results of the study have been reported more thoroughly in the reference (14). The methodology of the listening experiment follows the methodology presented in the reference (15).

2. MATERIALS AND METHODS

2.1 Research scheme

This was an experimental laboratory study where the subjects judged 44 impact *sounds*. Five different types of impact sounds (later: ***sound types***) were investigated. Each *sound type* was listened through nine different floor constructions (later: **floor types**). Several standardized and non-standardized SNQs were determined for each floor type based on their impact sound pressure level measured using tapping machine (16). Thereby, the data could be used to determine how well the SNQs predict the subjective judgments of each sound type. The independent variables were the SNQs determined for the nine floor types and the five sound types. The dependent variables were two subjective measures: *loudness* and *annoyance*.

2.2 Subjects

Fifty-five voluntary subjects (25 male, 30 female) participated in the experiment. The age varied from 20 to 57 years (mean 27, median 25, standard deviation 9). Subjects were invited via university student organizations. The subjects were told that the purpose of the experiment was to evaluate different sounds. The subjects signed a letter where they were informed that they are free to withdraw from the experiment and leave the room for any reason and that all materials gathered are treated confidentially by the research institute.

The presumptions were normal hearing ability, Finnish native language and currently residing in a multi-storey building. The latter condition was judged important because the experiment deals with sounds usually heard in multi-storey buildings and we wanted to avoid subjects who had no recent experience of living in such an environment. None of the subjects were occupied by authors' research institutes nor had participated in any prior experiment in the laboratory. The subjects were informed beforehand about the loudspeakers in the room. None of the subjects withdrew from the experiment.

2.3 Single-number quantities of floors

Our study involved eight various floor coverings F2-F9 installed on the top of the load-bearing concrete floor construction (F1) one after the other during the summer of 2012. The floor coverings were chosen to represent most commercial alternatives ranging from bare concrete floor to floating floor. The normalized impact sound levels L'_n [dB] were measured according to ISO 140-7 (16) using the tapping machine. The measurements done at Upofloor impact sound laboratory in Nokia have been described by Kylliäinen et al. (12). During these measurements, the receiving room was empty from additional sound absorbers – they were only used during natural impact sound recordings.

It seems probable that the unmodified standard tapping machine will remain as the official impact sound source in Europe (17). According to Gover et al (5, 6), the modified tapping machine, rubber impact ball or bang machine do not necessarily correlate better with subjective rating of walking sounds than the standard tapping machine. There is also some evidence suggesting that modifying the standard tapping machine or replacing it with some other sound source is not necessary, and the problematics of the correlation between the SNQs and subjective rating of floors should be approached be defining a better SNQ including a better reference curve (18). Because of these findings, only the standard tapping machine was used as a sound source in our study for the determination of the SNQ's of the nine floors. Eight SNQ's were determined for each floor type (Table 1) rounded to 0,1 dB (19). The impact sound spectra of the nine floor has been shown in Figure 1. The SNQ's were denoted as follows:

- $L'_{n,w}$ according to ISO 717-2 (19)
- $L'_{n,w} + C_I$ according to ISO 717-2 (19)
- $L'_{n,w} + C_{I,50-2500}$ according to ISO 717-2 (19)
- $L'_{n,w,Fas}$ starting at 100 Hz (20)
- $L'_{n,w,Fas,50}$ starting at 100 Hz (20)
- $L'_{n,w,Ger}$ (21)
- $L'_{n,w,Bod}$ (22)
- $L'_{n,w,Hag}$ (23)

Table 1 – The measured single-number quantities for nine floor types (12)

SNQ	F1	F2	F3	F4	F5	F6	F7	F8	F9
$L'_{n,w}$	79,9	77,7	58,7	59,1	58,5	42,7	50,1	43,2	41,3
$L'_{n,w} + C_I$	66,7	65,8	58,0	59,0	58,0	44,7	53,0	45,0	42,1
$L'_{n,w} + C_{I,50-2500}$	66,7	65,8	58,1	59,1	58,1	47,3	55,9	52,4	47,6
$L'_{n,w,Fas}$	68,4	67,3	59,4	60,4	59,4	44,7	52,1	45,2	43,0
$L'_{n,w,Fas,50}$	68,4	67,3	59,4	60,4	59,4	49,0	55,6	52,2	47,8
$L'_{n,w,Ger}$	66,4	65,6	58,4	59,8	58,6	41,9	50,3	43,6	41,5
$L'_{n,w,Bod}$	66,0	65,9	62,6	63,9	62,8	56,5	62,8	59,8	55,3
$L'_{n,w,Hag}$	68,7	67,8	60,7	61,8	60,5	54,5	61,2	61,0	56,1

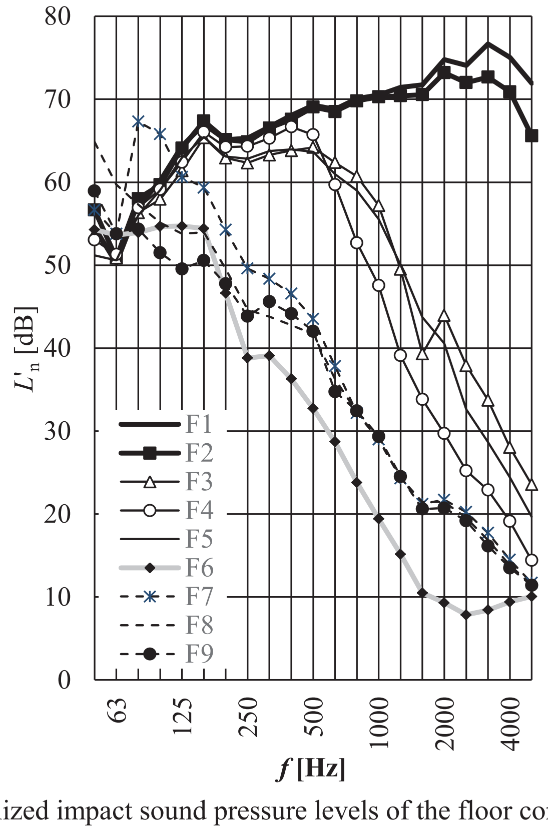

Figure 1 – Normalized impact sound pressure levels of the floor constructions (12)

2.4 Recordings of natural impact sounds

After the measurements with the tapping machine, additional sound absorbers were installed to the receiving room to enable the sound recordings of natural impact sounds in such a room acoustic environment which resembles normal living rooms. The room acoustics of the recording room corresponded relatively well with the reverberation time measured in Finnish living rooms and bedrooms (24). Five different impact sounds S1-S5 (independent variable: *sound type*) were recorded on the laboratory for each floor type F1-F9. The *sound types* were:

- S1 - Walking with hard shoes
- S2 - Walking with socks
- S3 - Walking with soft shoes
- S4 - Ball bouncing
- S5 - Chair moving

The walker was in all cases a male person (weight 86 kg, height 188 cm, age 22 years). The recordings of this walker were chosen to the listening experiments as the loudest of the three walkers described in (12). The two other walkers generated lower sound pressure levels but the shapes of the sound spectra generated by them were similar to the chosen walker.

Two-channel recordings were performed on the laboratory's receiving room. Simultaneously with the recordings of the five sound types, the equivalent sound pressure level spectrum of the sound was measured to enable the identification and adjustment of the recording in the audio filtering stage. In addition, a sixth sound type S6 was recorded to create the sounds for the rehearsal phase. These results were not analyzed. The levels of the stimuli exceeded the background noise level of the room and the quality of the sounds was good for post-processing. Forty-four twenty-seconds-long experimental sounds (later: *sounds*) were presented to the subjects. The spectra of the experimental sounds are shown in Figure 2.

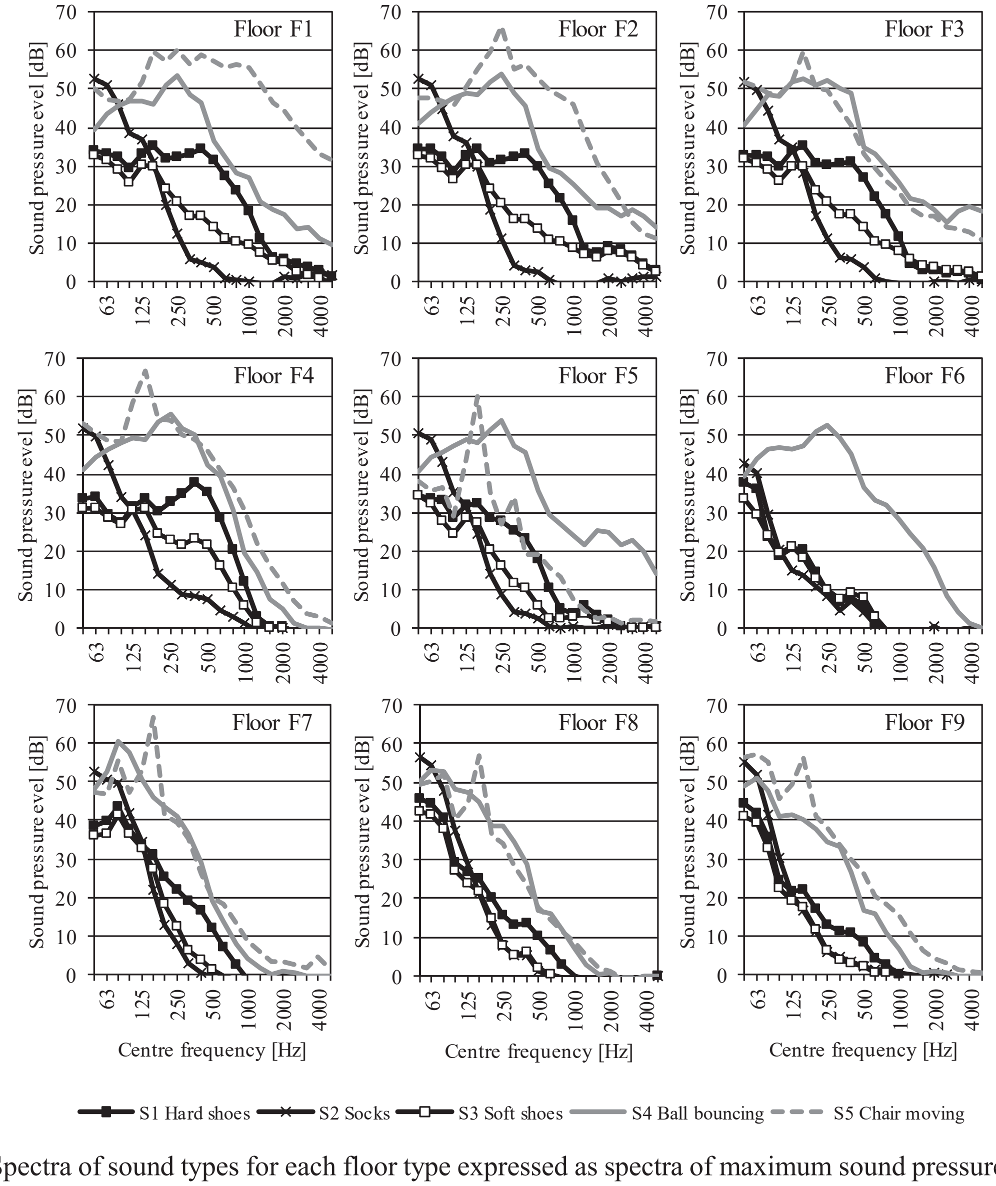

Figure 2 – Spectra of sound types for each floor type expressed as spectra of maximum sound pressure levels

2.5 Laboratory arrangements

The experiment was conducted in the psychoacoustic laboratory (30 m^2) at the Finnish Institute of Occupational Health. The background noise level $L_{A,eq}$ was approximately 23 dB which corresponded well with the mean value measured in Finnish living rooms (25). The reverberation time corresponded well with the mean value measured in Finnish living rooms (24).

The experiment concentrated only on the impact sounds from vertical direction. The subjects sat at the workstation during the experiment. The experimental sounds were reproduced by four active loudspeakers installed above the suspended ceiling in the periphery of the room. The speakers were not visible to the subjects. In addition, one subwoofer was located on the floor behind a heavy curtain.

2.6 Subjective measures

A software was programmed to pace the playback of the *sounds* and the questionnaires to the subjects. The subject controlled the experimental procedure (listening to sounds, answering the questionnaires, moving to the next sound) using this software.

The dependent variables of the experiment were three subjective measures: loudness, annoyance and acceptability. The subjects were instructed in the following way before starting the experiment: "*Imagine that you are alone at home in a multi-storey building in silence and peace. You are in a relaxed mind set. You are reading a magazine or a book or you are browsing the internet and you start to hear a sound from neighbouring dwelling upstairs*."

The background noise level of the room was larger than the equivalent level of several *experimental sounds* (Table 2). However, our pilot tests indicated that nearly all *experimental sounds* were audible because the stimuli were impulsive and the experimental sounds originated from the ceiling so that the *sounds* were easily audible despite the low equivalent level.

If the subjects judged the sound as inaudible, they were advised to select "0" in each response scale. The number of subjects giving a notation of an inaudible sound was small. Inaudible ratings were mainly given for the sounds S2F6 (25 subjects) and S3F9 (13 subjects). For other combinations, inaudible ratings were only occasional.

Before enabling the judgment of the sound samples, the subject was forced to listen once to the sound sample which lasted 20 seconds. During this period, the sentence "*You hear this kind of sound coming from your neighbour*" was shown in the display. Thereafter, three questions appeared on the screen. The sound sample was repeatedly played until the responses were given.

The loudness rating was given after a question "*How loud is the sound?*" The judgment was given on a scale from "0" to "10". The extreme alternatives were verbally labelled by "0: The sound is not heard", "1: Very silent" and "10: Extremely loud". The subjects were instructed to choose "0" if they could not hear the sound at all.

The annoyance rating was given after a question "*How annoying is the sound?*" The judgment was given on a scale from "0" to "10". The extreme alternatives were verbally labelled by "0: Not at all annoying because the sound is not heard", "1: Not at all annoying" and "10: Extremely annoying". The subjects were instructed to choose "0" if they could not hear the sound at all.

The acceptability rating was given after a question "*Would the sound be acceptable if it could be heard in your own home?*" The judgment was given on a four point verbal scale: "0: Completely acceptable because the sound is not heard", "1: Completely acceptable", "2: Acceptable to some extent", and "3: Definitely not acceptable". A four-point scale was used since the purpose of this question was to enquire about subject's ultimate opinion of the sound using a very simple verbal scale. In this paper, we report only the values of *loudness* and *annoyance* because the correlation coefficients of *acceptability* were very close to those of *annoyance* and the conclusions of our research would not be affected by including the *acceptability* data.

2.7 Experimental procedure

The experiment was conducted between November and December of 2013. One to three subjects per day were tested. The experiment took about 75–90 minutes including the hearing sensitivity test. All subjects had normal hearing ability. Thereafter, the subject moved to the listening room.

The familiarizing phase was used to let the subject to become familiar with the forthcoming *sounds* and their levels. This phase consisted of a collection of 15 *experimental sound* samples lasting only 8 seconds. Three samples of each of the five *sound type* were played. The most silent, the average level and the loudest *sound* were played in this order. The subjects were not yet given the possibility to judge the *sound* in the familiarizing phase.

The rehearsal phase was for practicing the subjective rating. The rehearsal period followed the same procedure as in the experimental phase. Nine *sounds* of the sixth sound type (S6F1-S6F9) were used. The results were not analyzed. Before the rehearsal phase, the subjects were instructed both orally and visually about the use of the rating scales. They were encouraged to use the whole scale.

During the actual experiment, the presentation orders of the *sound types* (S1-S5) and of the *floors* (F1-F9) were quasi-randomized between participants (Balanced Latin Square, five and nine alternative order choices respectively). Thus, all kinds of order effects were eliminated.

2.8 Statistical analyses

The primary purpose of our study was to determine the linear correlation coefficients between the subjective measures and the SNQs of the floors for each *sound type*. The responses were not normally distributed. Therefore, the correlation analysis was not conducted using the mean of the subjective ratings which has been done usually (5, 6, 15, 26). Instead, the correlation analysis was now conducted using the every individual response instead of the mean of all responses. The resulting R-values are smaller compared to those which would have been achieved by using mean ratings. Pearson's correlation coefficients, R, were determined, and the coefficients of determination, R^2, were reported. The correlation coefficient R was considered as statistically significant in the level of p=0,01 (55 data points) when the value exceeds R=0,34. The corresponding limit value for R^2 is 0,12.

3. RESULTS

The R^2 values between the single-number quantities (SNQ) and subjective measures (*loudness, annoyance*) are shown in Tables 2 and 3 for the five sound types.

Table 2 – The R^2-values between the single-number quantities and subjective *loudness* for five *sound types*. Bolding indicates that the value was statistically significant (p<.01, limit value 0.12).

SNQ	Frequency range	S1	S2	S3	S4	S5
$L'_{n,w}$	100–3150 Hz	**0,47**	0,03	**0,32**	0,11	**0,54**
$L'_{n,w} + C_I$	100–3150 Hz	**0,57**	0,05	**0,39**	**0,16**	**0,50**
$L'_{n,w} + C_{I,50\text{-}2500}$	50–3150 Hz	**0,56**	0,08	**0,37**	0,10	**0,53**
$L'_{n,w,Fas}$	100–3150 Hz	**0,57**	0,04	**0,38**	**0,16**	**0,50**
$L'_{n,w,Fas,50}$	50–3150 Hz	**0,55**	0,06	**0,37**	**0,13**	**0,53**
$L'_{n,w,Ger}$	63–2000 Hz	**0,58**	0,05	**0,39**	**0,15**	**0,49**
$L'_{n,w,Bod}$	50–3150 Hz	**0,60**	0,11	**0,41**	**0,13**	**0,44**
$L'_{n,w,Hag}$	50–3150 Hz	**0,45**	0,10	**0,29**	0,04	**0,51**

Table 3 – The R^2-values between the single-number quantities and subjective *annoyance* for five *sound types*. Bolding indicates that the value was statistically significant (p<.01, limit value 0.12).

SNQ	Frequency range	S1	S2	S3	S4	S5
$L'_{n,w}$	100–3150 Hz	**0,41**	0,03	**0,26**	0,09	**0,52**
$L'_{n,w} + C_I$	100–3150 Hz	**0,50**	0,05	**0,32**	**0,13**	**0,47**
$L'_{n,w} + C_{I,50\text{-}2500}$	50–3150 Hz	**0,49**	0,08	**0,31**	0,08	**0,51**
$L'_{n,w,Fas}$	100–3150 Hz	**0,49**	0,04	**0,31**	**0,12**	**0,47**
$L'_{n,w,Fas,50}$	50–3150 Hz	**0,48**	0,06	**0,31**	0,10	**0,51**
$L'_{n,w,Ger}$	63–2000 Hz	**0,51**	0,05	**0,32**	**0,12**	**0,45**
$L'_{n,w,Bod}$	50–3150 Hz	**0,53**	**0,12**	**0,35**	**0,11**	**0,43**
$L'_{n,w,Hag}$	50–3150 Hz	**0,40**	0,09	**0,25**	0,04	**0,51**

4. DISCUSSION

The best indicators of subjective loudness and annoyance regarding *sound types* S1, S3 and S5 were $L'_{n,w} + C_I$, $L'_{n,w} + C_{I,50\text{-}2500}$, $L'_{n,Fas}$, $L'_{n,Fas,50}$, $L'_{n,Ger}$ and $L'_{n,Bod}$. On the basis of average correlations of S1, S3 and S5, the highest R2 values (0,49) regarding subjective loudness were achieved with $L'_{n,w} + C_I$, $L'_{n,w} + C_{I,50\text{-}2500}$ and $L'_{n,Ger}$. Associating with subjective annoyance, the best averages (0,44) were achieved with $L'_{n,w} + C_{I,50\text{-}2500}$ and $L'_{n,Bod}$. As $L'_{n,w} + C_{I,50\text{-}2500}$ is among the best associated SNQs with both subjective measures, it could be suggested to be the most suitable SNQ if sound types S1, S3 and S5 were considered as the most important impact sound sources. This is supported by the results of other studies dealing with lightweight structures (7, 27). The differences between the SNQs were, however, small and practically as good SNQs might be $L'_{n,w} + C_I$, $L'_{n,Fas}$, $L'_{n,Fas,50}$, $L'_{n,Ger}$ and $L'_{n,Bod}$.

The lowest average R^2 values concerning *sound types* S1 (hard shoes) and S3 (soft shoes) were associated with $L'_{n,w}$ and $L'_{n,Hag}$. $L'_{n,w}$ does not take the frequencies below 100 Hz into account or weigh large deviations from the reference curve in the way of $L'_{n,w} + C_I$. This indicates that including the frequency range 50–100 Hz into a SNQ results in a better correlation between the SNQ and subjective rating also in the case of concrete floors. However, $L'_{n,Hag}$ which gives the strongest weight to the low frequencies did not correlate well with the subjective ratings of sound types S1 or S3. This might suggest that the low frequencies perhaps should not be weighted too much either.

The low correlation between all SNQs and subjective ratings of *sound type* S2 (walking with socks) can probably be explained on the basis of sound spectra. In the case of *sound types* S1, S3 and S5, the sound spectra were dependent on the floor type (Figure 2). Thus, the correlation between the SNQs and subjective rating were statistically significant. According to the earlier study (12), the spectra and sound pressure levels of *sound type* S2 are much less dependent on floor covering (Figure 2) than for other sound types. The difference between the highest and the lowest value of each SNQ was, however, large, between 10 and 38 dB depending on the floor type. Therefore, it is consistent that the correlation between the subjective rating of sound type S2 and SNQs was smaller than for other sound types where the spectral differences of the experimental sounds were larger. Another difference between *sound type* S2 (walking with socks) and the other *sound types* was the shape of sound spectrum. Other sound types involved sounds at mid-frequencies in addition to low frequencies. Walking with socks generated the highest sound pressure levels below 100 Hz with all floor types.

The result concerning *sound type* S4 (superball bouncing) differed from the result presented in the previous study (12). The analysis in Ref. (12) was based on maximum sound spectra and objective loudness of the sounds only, and the both these objective ratings of superball bouncing usually led to strong correlation with the SNQs. Temporal effects were not taken into account in (12) as it is usually expected that the experienced loudness of a time-varying sound is determined by the loudest momentary spectrum when the temporal modulation frequency is less than 10 Hz (28–30). Superball bouncing differed from walking as the ball hit the floor around 0,7 times per second, but the frequency of walking was twice as large. Other explaining factor for low correlation between *sound type* S4 and subjective rating is similar to *sound type* S2: according to Figure 2, the spectra are quite equal to each other for floor types F1–F6 even though the corresponding values of the SNQs differ by 10 to 27 dB.

5. CONCLUSIONS

A listening experiment regarding impact sound insulation of concrete floors was carried out. 55 people rated 44 sounds which were recordings of five impact sound sources directed to nine floor types. Eight objective single-number quantities (SNQs) were studied on the basis of correlation analysis between them and subjective ratings of loudness or annoyance.

Statistically significant correlation between the SNQs and subjective ratings were detected in the case of three sound types of five. Of the SNQs presented in ISO 717-2, the best indicators of subjective loudness and annoyance regarding walking with hard-heeled and soft-heeled shoes and chair moving were $L'_{n,w} + C_I$ and $L'_{n,w} + C_{I,50\text{-}2500}$. As well correlating indicators were also $L'_{n,Fas}$, $L'_{n,Fas,50}$, $L'_{n,Ger}$ and $L'_{n,Bod}$. The differences between these SNQs were small. As $L'_{n,w} + C_{I,50\text{-}2500}$ was among the best associated SNQs with both subjective measures, it could be suggested to be the most suitable SNQ if walking with hard-heeled and soft-heeled shoes and chair moving were considered as the most important impact sound sources. The use of $L'_{n,w} + CI_{,50\text{-}2500}$ is supported by the results of other studies dealing with lightweight structures.

The subjective rating of loudness and annoyance of the two other sound types, walking with socks and superball bouncing, were either weakly correlated or not correlated with the SNQs. These sound types cannot be considered as uncommon living sounds. In other words, the present SNQs do not cover all sound types sound types occurring in dwellings. Therefore, there is a need for development of SNQs of impact sound insulation which would correlate better with the general sound types.

ACKNOWLEDGEMENTS

This study was part of research project “User-oriented development of sound insulation in buildings ÄKK” (2012-2014) which was funded by Tekes – the Funding Agency for Technology and Innovation, Ministry of Environment and 8 companies of building industry. The authors would also like to thank steering group of ÄKK.

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