acoustics

MDPI

Review

Recent Developments in Investigating and Understanding Impact Sound Annoyance—A Literature Review †

Martina Marija Vrhovnik [1,2,*] and Rok Prislan [1,2]

[1] Innorenew CoE, Livade 6a, 6310 Izola, Slovenia
[2] Faculty of Mathematics, Natural Sciences and Information Technologies, University of Primorska, Glagoljaška 8, 6000 Koper, Slovenia
* Correspondence: martina.vrhovnik@innorenew.eu
† This paper is an extended version of our paper published in "Aspects of Quantifying Impact Sound Annoyance" in Proceedings of Forum Acusticum, Torino, Italy, 11–15 September 2023.

Abstract: Impact sound, particularly prevalent indoors, emerges as a major source of annoyance necessitating a deeper and more comprehensive understanding of its implications. This literature review provides a systematic overview of recent research developments in the study of impact sound annoyance, focusing on advances in the assessment of impact sound perception through laboratory listening testing and standardization efforts. This review provides a detailed summary of the listening setup, assessment procedure and key findings of each study. The studied correlations between SNQs and annoyance ratings are summarized and key research challenges are highlighted. Among the studies, considerable research effort has focused on the assessment of walking impact sound and the use of spectrum adaptation terms, albeit with inconsistent outcomes. Comparison with the previous literature also shows the influence of spatial and temporal characteristics of impact sound sources on perceived annoyance, with higher spatial fidelity leading to higher annoyance ratings. Furthermore, it has been shown that the consideration of non-acoustic factors such as noise sensitivity and visual features are important for the assessment. This review provides a comprehensive overview of recent advances in the understanding and assessment of impact sound annoyance and provides information for future research directions and standardization efforts.

Keywords: impact sound; psychoacoustics; annoyance ratings; sound reproduction methods

check for updates

Academic Editors: Yat Sze Choy and Jian Kang

Received: 19 September 2024
Revised: 14 January 2025
Accepted: 25 March 2025
Published: 14 April 2025

Citation: Vrhovnik, M.M.; Prislan, R. Recent Developments in Investigating and Understanding Impact Sound Annoyance—A Literature Review. *Acoustics* **2025**, *7*, 21. https://doi.org/10.3390/acoustics7020021

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Subjective discomfort due to noise exposure can lead to physiological health effects such as high blood pressure and cardiovascular diseases [1]. In addition, noise can cause stress, discomfort and annoyance, which affect our well-being and productivity and thus have indirect and long-term negative effects on health [1]. Noise also has a significant social impact when considering the annoyance caused by noise from neighbors [2]. As we spend much of our time indoors, where impact noise is considered one of the most disturbing sounds [3], its effect on our well-being should be better understood. Consequently, efficient sound insulation is considered a major goal of building physics.

To assess the quality of a building in terms of impact sound, several psychophysical indicators have been developed, some of which have found their way into standardization. These Single Number Quantities (SNQs) are intended to relate the sound pressure generated by a standardized impact sound source to the subjective response of the listeners, i.e., the users of the building. Unfortunately, several shortcomings of these SNQs have been

identified over time, calling into question their relevance and suggesting their revision. The historical argument for this is that SNQs were mainly developed for the assessment of concrete buildings [4]. However, studies looking at lightweight buildings show that SNQs correlate poorly with perceived annoyance [4]. The greater challenge in this context appears to be the assessment of the low-frequency components [5], which is particularly difficult to evaluate. This is relevant given the increasing popularity of lightweight buildings, which contain more and more technical services and equipment that generate more installation noise, including sources with strong low-frequency components. In this context, the discussion about different standardized impact sound sources (tapping machine, rubber ball) and their suitability to represent real sources (e.g., walking, jumping) also becomes relevant [6].

In addition, the standardized SNQs used can vary greatly from country to country. Rasmussen and Rindel gave a historical overview of the development and complexity of legal sound insulation requirements [6,7]. They showed that the differences between the individual countries are extensive, so much that the requirements between them are not comparable with each other. The legal requirements for sound insulation, which are based on EN ISO 717:1996 [8], provide for a variety of evaluation methods. This conflicts with the need for an assessment system that can be adequately applied to both light- and heavyweight structures. In addition to the standardized SNQs, their modified versions are often developed, mainly in the context of various research projects. Consequently, the range of SNQs examined in this literature review is also broad and difficult to contain, which directly confirms the conclusions of Rasmussen and Rindel.

To overcome the confusion, more relevant SNQs need to be developed, which means that a better understanding of the subjective auditory perception of impact sound is required. However, exploring perception brings its own challenges. Most importantly, we have a short auditory memory: in situ comparisons at longer time intervals between listening sessions are neither valid nor reliable. The comparison and evaluation of sound scenes by humans must therefore take place under controlled laboratory conditions [9]. Such laboratory listening tests can be technically very complex, as the listening conditions must be accurately reproduced. In addition, the approach is highly interdisciplinary, as methods from the world of psychology must be applied, while the data are only relevant in a statistical sense. Ultimately, the responses obtained would correlate well with an SNQ, from which its relevance to the assessment of perceived annoyance can be derived.

On this endeavor, several non-acoustic factors must be taken into account, such as noise sensitivity of individuals and visual features presented during the listening tests. In fact, it is estimated that they

> "... account for up to one third of the variance observed in annoyance reactions." (Fenech, 2021, p. 2) [10].

Which factors are considered acoustic or non-acoustic is a matter of discussion and will be defined in a new ISO Technical Specification on non-acoustic factors, which is in preparation [10].

In 2018, Vardaxis and Bard published a review article on

> "... studies that approach acoustic comfort in living spaces by linking acoustical data and subjective responses in laboratory tests." (Vardaxis and Bard, 2018, p. 1) [11].

As the review focused on impact sound, it was taken as a starting point for this review. The aim of this review is to identify research priorities for the next few years and use the findings to highlight progress and inconsistencies between studies and in comparison to the studies [12–26] examined in Vardaxis and Bard (2018). It describes the objectives and goals of each study, the methods used, the data and results, and the conclusions drawn. A brief summary of the content of each study is provided in chronological order,

while the similarities and differences between the studies are discussed. To provide an overview, basic information is also presented in the form of tables. Figure A1 summarizes the listening test procedure and reproduction method, lists the dependent variables studied and the SNQs used. It also contains the calculated correlations between the dependent and independent variables and their statistical significance. Table A1 lists all SNQs used in the studies, their definitions and the sources of their publication.

2. Method

The databases Scopus, World of Science and ResearchGate were used to search by the author for articles and conference proceedings, published after 2018 in English, between the 2nd and 20th of May 2023. The search was based on several combinations of the following keywords: *impact*, *noise*, *sound*, *annoyance*, *buildings and single number quantity.*

The experimental studies to be considered had to perform listening tests for the subjective assessment of impact sound annoyance under laboratory conditions. Laboratory conditions means that the reproduced impact sound was recorded and played back through headphones or loudspeakers in a controlled environment.

Standardized and real impact sound types were considered as sound stimuli recorded in field or transmission chamber recordings. A further prerequisite for the inclusion of a study was also the investigation of correlations between at least one SNQ and the collected annoyance ratings.

As a systemic method of data collection, the PRISMA diagram flow is applied [27]. With the help of the previously mentioned keywords used in the databases and a "snowball" search from the citations of the already identified references, a total of 251 studies were identified. There were 78 duplicates removed, leaving 173 studies for the screening process. In total, 139 articles were excluded as only peer-reviewed articles and conference proceedings with the previously mentioned inclusion criteria were allowed to be considered. After this exclusion, 34 articles remained for retrieval. Then, 15 articles were screened for eligibility. One article was then excluded because it did not contain statistical data. Finally, this review presents 14 peer-reviewed articles and conference proceedings about the assessment of subjectively perceived impact sound annoyance with listening tests (see Figure 1).

With regard to the discussion and assessment of systematic errors in the respective studies, it is often difficult to formulate a well-founded ranking on the basis of the information provided. For example, a small number of participants and their selection procedures can be critical and lead to biased results (see Section 4.7). Such information is often not provided or difficult to extract from the studies.

However, focusing on peer-reviewed articles, we assume that selection bias is limited. This applies in particular to the correlation values between the qualities used and the selected SNQs.

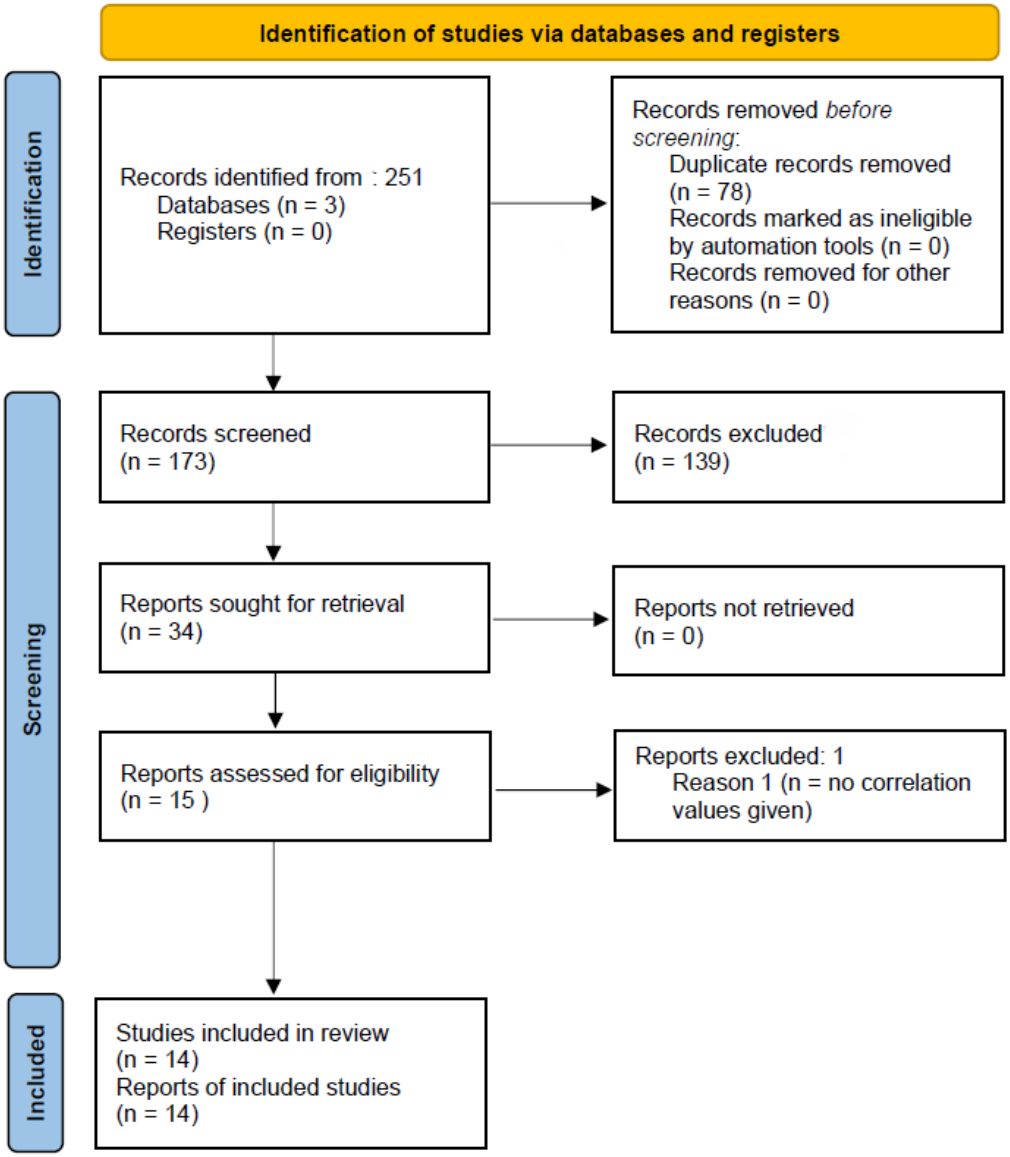


Figure 1. PRISMA flow chart for studies investigating impact sound annoyance with listening tests.

3. Results

Öqvist et al. identified low-frequency components of impact sound as a limitation for the predictive power of standardized SNQs [28]. In particular, walking sounds that have a pronounced low-frequency component tend to be perceived as more annoying in lightweight than in heavyweight structures. The objectives were to verify (1) whether frequencies between 20 and 50 Hz are important for walking noise annoyance and (2) whether the modified spectrum adaptation term improves the correlation with perceived annoyance. In total, 24 participants took part in a two-part listening test in which they compared the differences in the low-frequency content of impact sound recorded in a heavy- and a lightweight construction. The impact sound types used were walking with socks and in Oxford shoes. The in situ measured values of $L'_{nT,w}$ of 47 dB for heavyweight and 44 dB for lightweight buildings and the values of $L'_{nT,w} + C_{I,50-2500}$ of 48 dB for heavyweight and 49 dB for lightweight buildings fulfilled the Swedish requirements of $L'_{nT,w}$ and $L'_{nT,w} + C_{I,50-2500} \leq 56$ dB. Considering the ratings, the two construction types should achieve a similar level of protection against walking noise, although the spectra of the concrete construction showed lower levels below 100 Hz. A two-part listening test was carried out. In the first part, participants were

asked whether they perceived a difference in annoyance between the original recorded walking sound and its high-pass filtered version filtered at cut-off frequencies of 25, 31.5, 40, 50 and 100 Hz in 20 randomized comparisons. This was used to investigate which low-frequency third-octave bands are relevant for the perception of a difference in annoyance. In the second part of the listening test, the participants had to decide which of the two presented stimuli was more annoying and whether the perceived difference was small or clear. The comparison was also made considering the modified version of the standardized SNQ $L'_{n,w} + C_{I,50-2500}$ developed by Ljunggren as part of the Akulite project, in which the weight is increased for frequencies below 50 Hz and above 400 Hz [29]. Öqvist's results suggest that this modified SNQ overestimates the lower frequencies when the measurement uncertainty is greater between 20 and 40 Hz. The uncertainties of the SNQs were evaluated as probability distributions of the deviations between the single simulated values and the mean value of the simulated SNQs [30].

Park et al. focus on noise sensitivity, which as a non-acoustic factor, also contributes to impact sound annoyance [31]. They investigated how noise sensitivity affects the perception of noise annoyance and how it also affects physiological responses to noise. Based on the subjects' self-evaluated noise sensitivity, 34 participants were divided into groups with low and high noise sensitivity. In addition, three types of physiological responses were measured during the listening test: heart rate (HR), electrodermal activity (EDA) and respiratory rate (RR). As impact sound types, referred to as transient noise, a real source (footsteps) and a standardized source (rubber ball) were recorded binaurally with a head-and-torso simulator. In addition, road traffic noise was recorded, which represents the stationary noise from outside and was used for comparison. The duration of listening differs from the other included studies. Whereas in the other studies the duration was only a few seconds, in this study it had to be drastically longer to provoke significant variations in the physiological responses. The investigated sound pressure levels of the floor impact sounds, L_{AFmax}, were 40, 50 and 60 dBA and those of the road traffic noise were 40 and 60 dBA. The participants gave their answers to their perceived annoyance on an 11-point scale (0: "not at all" to 10: "extremely"). It was found that the noise annoyance ratings increased for all noise sources when the noise level was increased. The participants in the high noise sensitivity group had higher annoyance ratings than the participants in the low sensitivity group. In addition, the high sensitivity group showed more pronounced changes in their physiological responses. The measured physiological responses were calculated for different noise exposure durations from 30 s to 50 min. Over time, there was a strong habituation with an initial increase in EDA and RR and a rapid decrease after 30 s. Another finding is that the physiological responses were not influenced by the type of noise source or its sound pressure level.

Frescura and Lee also focused on noise sensitivity as a key variable in the assessment of annoyance [32]. They studied annoyance from a combination of impact and airborne sound sources while monitoring four physiological responses: facial electromyography (fEMG), electrodermal activity (EDA), heart rate (HR), and respiration rate (RR). The impact sound stimuli were recorded on a lightweight timber joists floor with four different impact sound sources: an adult walking at (1) normal pace, (2) 108 steps/min and (3) fast pace (132 steps/min), and (4) a running kid. The airborne sound sources were speech and piano playing. Their spectral characteristics were modified to emulate lightweight partitions with good, medium and poor sound insulation performances ($R_w = 52, 43, 33$ dB). Before the listening test, 20 participants evaluated their noise sensitivity using the NoiseQR questionnaire [33]. The listening test consisted of four sessions. In three sessions, each noise source (impact sound and airborne sound) was presented for 15 min. In the fourth session, impact sound and airborne sound were presented all at once. At floor ratings $L'_{nT,w}$ = 30–45 dB,

the annoyance increased when airborne noise corresponding to $R_w = 43$ dB and 33 dB was added. At $L'_{nT,w} = 45$ dB, the influence of airborne sound on the annoyance ratings was lower. It was found that the sound pressure level could not fully explain the perceived annoyance, as the annoyance ratings for normal and fast walking were rated as less annoying at $L'_{nT,w} = 45$ dB than at 40 dB. Therefore, the sound quality metrics of loudness, sharpness, roughness and fluctuation strength were additionally evaluated. Loudness and sharpness showed the highest correlation with the annoyance ratings, i.e., the higher the loudness and the higher the sharpness, the greater the annoyance.

In addition to loudness, spectral, spatial and temporal characteristics of impact sound also influence the impact sound perception as investigated by Jo and Jeon [34]. They evaluated the influence of spatial and visual cues on annoyance ratings in a virtual reality environment. Recordings of a standardized rubber ball moving through an upper room to represent a continuous walking sound were played through headphones (1) as a mono sound source, (2) binaurally with an applied head-related transfer function (HRTF), (3) in mono with visual information via a head-mounted display (HMD) and (4) binaurally with an applied HRTF and with visual information via the HMD. The participants rated their annoyance of impact sound at different SPLs and different temporal decay rates. The effects of the directional information of the noise source and the visual information on the participants' response were also investigated. The correlation between $L_{A,Fmax}$ and annoyance showed that annoyance ratings were significantly higher with binaural playback or with binaural playback in combination with visual information (cases 2 and 4). The allowance limit, measured in SPL dBA, at which half of the participants could no longer tolerate the noise, was significantly lower in the binaural case (cases 2 and 4) than in the mono case (cases 1 and 3). The study concluded that noise sensitivity, and therefore annoyance, was higher when directional and visual information was provided.

Jeong et al. investigated heavyweight impact sources such as the tapping machine, walking or the rubber ball, which have been less studied than their lightweight counterparts. (The authors define the impact source tapping machine as a heavyweight source [35]. According to ISO16283-2 (p. vi) [36], the tapping machine "... can be used to assess a variety of light, hard impacts...". Here, it is not defined as a heavyweight impact source. Furthermore, other studies, such as Trapet et al. (2020) [37], define the tapping machine as a lightweight source.) They conducted two listening tests in which the seven SNQs were evaluated. The first experiment, which took place in Korea, involved 211 participants. In total, 101 participants rated their perceived annoyance from rubber ball impact noise in a heavyweight building scenario, while 110 participants rated adult jumping and rubber ball impact noise in a lightweight building scenario. As in the previously described studies, annoyance ratings increase with increasing noise levels for all noise sources and building types. The rubber ball impact noise was found to be similarly annoying in heavy- and lightweight buildings, with almost identical regressions for the rubber ball and jumping in lightweight buildings. The authors imply that the sound pressure level contributes more to annoyance than the type of impact source or building type. In the second experiment, conducted in Europe, 43 participants rated their perceived annoyance from the two types of noise sources in heavyweight and lightweight constructions. There were no significant differences between the building types when comparing the noise annoyance caused by the impact of the rubber ball. In the lightweight construction, similar annoyance ratings were found for the rubber ball and jumping. The authors hypothesized that the similarity in annoyance ratings for the different building types may be due to similar spectral characteristics of the sound stimuli. The SNQ $L_{iA,Fmax}$ showed the highest correlation values, while the SNQ LL_z, also known as Zwicker loudness [38], had the lowest correlation value for the rubber ball case. The study concludes that SNQs based on sound

energy, especially $L_{iA,Fmax}$, have higher correlation values than SNQs based on loudness, such as L_{Lz}, N_5 or N_{max}. They recommend the use of $L_{iA,Fmax}$ because it does not require frequency analysis and the application of a reference curve. This makes $L_{iA,Fmax}$ a practical SNQ, i.e., it is easy to measure and calculate.

Kyllianen et al. took a different approach to finding the most appropriate SNQ for assessing annoyance with the aim of developing new SNQs with a high correlation to subjectively perceived annoyance [39]. The requirement was that the new SNQs should consist of $L'_{n,W}$ or $L'_{nT,W}$ and a newly defined spectrum adaptation term for the frequency range 50–2500 Hz. The reference spectra for five impact sound types on nine floor types were derived by mathematical optimization. Based on the reference spectra of each impact sound type and the psychoacoustic experiment conducted, new spectrum adaptation terms were determined for each impact sound type. In addition, an optimal reference spectrum was derived on the basis of the five reference spectra, which can be used to predict the annoyance for all impact sound sources. The results of the listening test showed that each of the new SNQs as well as the optimized SNQ had a higher correlation with the annoyance ratings compared to the standardized SNQs from ISO 717-2. In particular, when walking with socks, one of the most common sources of impact sound in the built environment, the optimized SNQ had a significantly higher correlation with the annoyance ratings than the standardized SNQ, which showed a very poor correlation.

A large study on impact sound in multi-unit residential buildings (MURBs) was conducted by the National Research Council of Canada with the main objective of gaining qualitative data for the development of improved SNQs that can be used in building codes [37]. It was carried out by Müller-Trapet et al., who evaluated the annoyance from various heavy- (rubber ball, walking) and lightweight (tapping machine) impact sound sources used on 12 floor assemblies, including cross-laminated timber, timber frame floors with various coverings, interlayers and ceiling linings. Correlations were calculated between the annoyance ratings and impact insulation class (IIC) according to ASTM E989 [40], $L_{n,w}$ and $L_{AF,max}$ as well as the spectrum adaptation terms $C_{I,50}$ and $L_{CF,max}$ for each sound type. Rubber ball drops from 1 m height showed the highest correlation with $L_{AF,max}$, while the tapping machine correlated better with ICC and $L_{n,w}$. However, the correlation values for the tapping machine and for rubber ball drops from 10 cm height improved when $C_{I,50}$ was added. A large difference was found in the correlation between impact sounds when walking with shoes and when walking barefoot. While all SNQs correlated equally well when walking with shoes, none of them correlated well when walking barefoot. Instead, the correlation improved for barefoot walking when the evaluation was performed with an $L_{CF,max}$ instead of $L_{AF,max}$. This indicates that the evaluation of the low-frequency content is most important for this type of impact sound. In contrast, the averaged $L_{n,w} + C_{I,50}$ shows the highest correlation for all other impact sound sources.

Hongisto et al. investigated whether the use of floor coverings on heavyweight floors reduces the perceived annoyance caused by real impact sounds [41]. The question was whether the standardized SNQs ranked the tested floors in the same order as a subjective evaluation would. It was also tested whether the value of the resonant frequency, f_0, of a floating floor influences the perception. On six typical floor types, four floating and two non-floating floors, four natural impact sounds were recorded: (1) basketball bouncing, (2) chair moving, (3) walking with shoes and (4) walking with socks. After the listening test, the collected subjective annoyance ratings and the objectively measured results were analyzed and a ranking of floor coverings for each natural impact sound was made. f_0 for the six floor types were in the 1/3 octave bands of 63, 100 and 125 Hz. The results showed that the beneficial reduction in perceived annoyance of a floating floor depends

on the type of impact sound. The aggregation of all four floor types showed that the most annoying floating floor had an $f_0 = 125\,\text{Hz}$ and the least annoying had an $f_0 = 63\,\text{Hz}$. This shows that the f_0 of a floating floor should be sufficiently low. For the impact sound types, the subjective and objective results differed for basketball bouncing and walking with socks, but showed high correlation values for chair moving and walking with shoes, indicating that the standardized SNQs could not correctly rank the six floor types for all four sound types. This was particularly evident for walking with socks, where the ranking of annoyance did not correlate well with the ranking based on the SNQ values.

In their study, Amiryarahmadi and Kropp presented a virtual design studio that enables realistic reproduction of the low-frequency components generated by barefoot walking [42]. Referring to the results of the Swedish Akulite research project [43], the authors argue that the perception of walking on wooden floors is one of the most disturbing sounds, especially in multi-storey buildings, and that the (un)conscious interpretation of the sounds influences the level of annoyance, stress and cognitive performance. The low-frequency sound pressure generated by walking is highly case-specific and depends on the exciting force at a time-varying position, the response of the floor at a particular position and the response of the room. Therefore, the authors have designed a listening environment that simulates real floors and consists of a living room-like studio with a hidden loudspeaker grid above the ceiling. During the listening test, it is possible for the participant to move freely through this environment. Footstep sounds from ten different (mainly) lightweight floor structures were reproduced. Loudness, distinctness, thumping, reverberation, annoyance and naturalness were the attributes available to rate the perceived impact sound. To investigate how plausible the auralization was perceived, the ratings of the naturalness were particularly important, with 75 % of the ratings of 4 or more, 57 % between 5 and 7 and 15 % of 7. The authors concluded that the participants were not able to distinguish between the real and the simulated sound field and that the reproduction was therefore perceived as plausible. Reverberation and thumping were rated differently depending on the floor design, implying that they depend on the material and structural properties of the floor. Distinctness showed no significant variation, leading to the assumption that the meaning of the term is not clear. The reproductions with the lowest loudness ratings were rated as the most plausible. Annoyance was positively correlated with loudness, i.e., the louder the stimuli were, the higher the annoyance ratings were. The comparison of the subjective results with the SNQs ($L_{n'T,w}$, $L_{n'T,w} + C_{I,50-2500}$, and $L_{n'T,w} + C_{I,20-2500}$) shows that for about half of the lightweight floors studied, no SNQs could predict the perceived annoyance. The authors concluded that the lack of correlation means that the perceptual evaluation of impact sound is of great importance and further investigation is required.

Since the COVID-19 pandemic, the work from home policy in Korea has changed, resulting in more employees working from home. This has led to an increase in complaints from neighbors about noise. Shin et al. found that the heavyweight impact sound of footsteps in reinforced concrete apartment buildings is a major source of stress [44]. The goal of their study was to present representative spectra of standardized impact sound sources in multi-dwelling buildings together with the subjective responses. The authors measured the impact sound and spectra of 140 Korean households. In total, 80 households were in buildings that met the national legal criteria for a slab thickness of at least 210 mm and 60 buildings were built before 2004, when this legal requirement was introduced, and had a slab thickness of less than 210 mm. To determine the representative spectrum, the recordings of the standardized heavyweight impact sources tire and rubber ball within the 63–500 Hz band were analyzed. The authors performed a cluster analysis of the measured data using the k-means clustering algorithm. The configuration of the frequency

characteristics was significant and for the analysis they used the difference in SPL within the bands (1) 63–125 Hz, (2) 125–250 Hz and (3) 250–500 Hz. For each impact sound source, four clusters were found, based on which the typical spectra of rubber ball and tire sound were acquired. The four spectra represented different thicknesses: spectrum 1 was mainly used for the slab thickness of 210 mm, spectrum 2 and 3 for slab thicknesses between 110 and 180 mm and spectrum 4 included both slab thickness conditions. In addition to recordings of two standardized impact sound types (tire and rubber ball), two real sound sources (adults walking and child running) were recorded in a household with a 180 mm thick slab. In the listening test, 105 participants rated the perceived annoyance of 80 stimuli in about 60 min. Based on the results of the listening test, five classes of heavyweight impact sounds were developed. As the SNQs can differ by up to 6 dB depending on the spectrum type in the same class, the importance of structural characteristics for heavyweight impact sound is emphasized. The authors concluded that no standardized impact sound source can properly reproduce walking and running, which means that future research should analyze the impact sound of footsteps generated in different building types. This would eventually make it possible to develop a standardized representation of impact sound from walking and running.

Frescura et al. investigated the spatial and temporal factors for the subjective evaluation of sound sources [45]. Since the left hemisphere of the brain processes temporal factors and the right hemisphere spatial factors, they hypothesized that sounds that simultaneously vary spatial and temporal factors may cause greater annoyance due to stimulation of both hemispheres. Before listening, participants were divided into a low or high sensitivity group using the NoiseQR [33] and provided information on their demographic data, attitude towards neighbors and circadian rhythm type. The footstep sound was recorded by two people wearing socks while walking separately on a lightweight timber joist floor. For the stimuli with varying interaural cross-correlation (IACC), three walking trajectories (figure-of-eight, straight line and on three spots) and two walking paces (normal pace: 1.8 s^{-1} and very slow pace: 1 s^{-1}) were recorded. The listening test consisted of two sessions in which the footstep sound was evaluated at normal and very slow pace. By projecting images of a living room with natural or artificial light, each stimulus, within a test session, was presented once at a day (living room with natural light) and once at a night (living room with artificial light) condition. When walking at a normal pace, the rating of annoyance increased with increasing IACC. The stimuli in the first session were divided into three groups according to their IACC value. Group 1 had the lowest IACC values and also significantly the lowest annoyance ratings. Group 2's IACC values were higher and also corresponded to higher annoyance ratings. Group 3 had the highest IACC values and also the highest annoyance ratings. The observed influence of IACC on annoyance was therefore significant. The differences in annoyance in relation to the time of day were also significant, with annoyance ratings being higher at night. The walking pace also influenced the assessment of annoyance, with a very slow pace being perceived as more annoying than a normal pace. In terms of non-acoustic factors, the annoyance ratings of the low sensitivity group were significantly lower than those of the high sensitivity group both during the day and at night conditions. The chronotype of the participants was also used as an explanatory factor in this study, with E-type (nocturnal type) participants having significantly higher annoyance ratings than M-type (morning type) participants. Participants with a negative attitude towards neighbors also reported higher levels of annoyance compared to participants with a positive attitude.

Kim et al. conducted a psychoacoustic experiment for impact sounds that vary in duration, number or level based on impact sounds of children jumping [46]. The sounds with an irregular pattern relevant in real-life scenarios were used to determine evaluation

indices. The recorded single impact stimuli (SIS) were edited in terms of duration, number of impacts and impact pattern to generate multi-impact stimuli (MIS). The listening test then compared SIS and MIS at different $L_{iA,Fmax}$ levels by having the participant select the more annoying impact source. At SIS levels of 57 and 62 dB, all participants responded that MIS was more annoying, indicating that despite equal or lower MIS levels, the effect of duration became significant. At 77 dB, however, all subjects felt annoyed by SIS, indicating that the sound level became the dominant factor when the level difference became very large (+20 dB). Higher annoyance was also observed with a higher number of impacts and stimuli of longer duration. Regarding the determination of valid indices, it was found that even with equal $L_{iA,Fmax}$ values of SIS and MIS, the MIS can lead to higher annoyance ratings. This indicates that impact sounds that differ in the number of impacts, duration or level cannot be directly compared. Furthermore, the subsequent statistical calculations showed that L_{Aeq} and L_{AE} had a higher correlation for MIS. One explanation for this could be that these two indices reflect the duration and energy of the impact sound, in contrast to $L_{iA,Fmax}$, which only indicates the simple maximum level.

Panosso and Paul focused on the problem that the standardized tapping machine cannot reproduce the low-frequency content of real impact sound sources, especially that of footstep sound [47]. The authors investigated an alternative, heavyweight impact sound source, in this case a calibrated tire, which can better reproduce this frequency content. They also tried to find out which objective indicators can be used to correctly predict the subjective evaluation. In total, 56 listening samples were recorded with 2 floor coverings (porcelain and wood), 13 resilient layers and 2 impact sound sources (tapping machine and calibrated tire). In the listening test, an impact sound recorded for a floor without a resilient layer was used as a reference sound sample, which was designated as the anchor. (The use of the anchor has been recommended in [48]). A listening test session consisted of thirty sound samples divided into six blocks of five samples each with different resilient layers. The participants compared five impact sound samples with the anchor. For each comparison, the annoyance and loudness were rated in relation to the rating of 100 assigned to the anchor. For the case of the tapping machine, it was found that the type of floor was not relevant and that the subjective results correlated very well with $L'_{nT,w}$ and especially with $L'_{n100-3150Hz}$. The latter could therefore be used as a predictor for the subjective perception of annoyance and loudness. The correlation values for the calibrated tire were not as consistent. For the porcelain flooring, the calibrated tire achieved high correlations between the subjective ratings and $L_{i,Favg,Fmax}$ and $L_{i,Fmax,50-630Hz}$. $L_{AF5\%}$ and $L_{AF10\%}$ had higher correlations for loudness than for annoyance. The calibrated tire impacts on the wood flooring did not correlate well with annoyance, while they showed a better, but still insufficient, correlation for loudness with $L_{AF5\%}$ and $L_{AF10\%}$. The authors concluded that the tapping machine relates better with the subjective responses, while the calibrated tire can be a valid sound source for specific measurement setups.

Frescura et al. did not perform listening tests, yet their research is relevant to this study as they investigated the relationship between SNQs and impact sound ratings for different floor structures [49]. The frequency characteristics of two standard (tapping machine and impact ball) and six real impact sources (three different types of footsteps and three different falling objects) were compared to assess whether standardized impact sources can represent real impact sources. The correlation coefficients between the standardized SNQs and the impact sound ratings (L_{Aeq}, L_{AFmax} and L_N) were calculated in one-third octave bands between 50 Hz and 1 kHz. The correlation coefficients between tapping machine and impact ball and the real impact sources were similar for floating floors and suspended ceilings. For all real impact sources, the correlation between the standardized SNQs for tapping machine and impact ball was significant. The correlation values with

the energy-based impact sound ratings L_{Aeq} and $L_{A,Fmax}$ were higher than those with the loudness level L_N. The authors concluded that the standardized SNQs for the tapping machine and the impact ball

> "... assessed the lightweight floor structures adequately considering the realistic situations with different real impact sources" (Frescura et al. (2021), p. 11) [49].

Regarding the results for the real impact source type of walking, variations in pace or footwear had little effect on the correlation values between SNQs and impact sound ratings. However, in the context of this literature review, it must be emphasized that these conclusions may have been drawn because only the spectral sound characteristics were considered, while a perceptual evaluation was not performed.

4. Discussion

4.1. Impact Sound Type

When considering all studies, six types of impact sources were used. Jumping was used three times, chair moving two times and a running child one time as a real impact source. As a standardized counterpart, a ball was used eight times (most frequently), a tapping machine three times and a calibrated tire two times. Hongisto et al. concluded that the tapping machine represented walking better than the impact ball [41]. In contrast, Jeong et al. found no significant differences in the correlation value for annoyance when comparing ball and jumping [35].

In terms of research intensity, walking is the most frequently investigated and evaluated impact sound source type. In 10 out of 13 studies [28,31,32,34,37,39,41,42,44,45], the correlation between the annoyance caused by walking and various descriptors was investigated. One reason for the intensive research on this aspect could be the earlier reports by Vardaxis and Bard [11] of a low correlation between walking sound and all standardized SNQs. In addition, walking appears to be one of the most annoying types of impact sound sources due to its dominant low-frequency component ([42,44]). In some studies [42,44], walking annoyance was the focus of the investigation, while in other studies walking was investigated together with several other types of impact sound sources. In most studies [37,39,41,42], none of the standardized SNQs used correlated well with walking annoyance, regardless of whether they were conducted on heavy- or lightweight structures. Based on this literature review, there appears to be no significant progress in correlating SNQs with walking impact sound annoyance, which therefore remains an important aspect that should be investigated further.

In this context, several studies have also taken into account the sound type impact or rubber ball. The study by Lee et al., already discussed in the literature review by Vardaxis and Bard, concludes that L_{Amax} is a good predictor of walking annoyance [50]. However, the author of this literature review points out that different descriptors were mentioned as most suitable in the individual studies (see Figure A1). Like Shin et al., the authors therefore conclude that there is still no impact source that can replace walking in its entirety.

4.2. Low Frequency Consideration

The results regarding the evaluation of low-frequency content are contradictory. The results of Shin et al. [44] indicate that no standardized impact source can plausibly reproduce the acoustic attributes of a real impact source. It would therefore be necessary to develop a standardized source that can more realistically represent real impact sources. On the other hand, Panosso and Paul [47] report that $L'_{nT,w}$ and $L'_{n100-3150Hz}$ correlate well with the perceived annoyance of a tapping machine. It is interesting to note in this context that the calibrated tire with a low frequency content, which better represents walking, did not achieve a higher correlation than the tapping machine. Öqvist et al. [28] empha-

sized the importance of including frequencies down to 20 Hz when assessing walking with socks in wooden buildings. However, the modified SNQ developed in the Swedish Akulite project for the evaluation of low frequencies and included in the Swedish standard SS 25267:2015 [51] weights the low frequencies too heavily and is measured with large uncertainties.

This is in line with the findings of Larrson et al. [52] that the measurements rely on a statistical description of the sound field, which is not justified in the low-frequency range due to the low modal density and the strong dependence on the measurement position. Lack of diffuseness is in fact a challenge for insulation measurements [53]. Hongisto et al. [41] have also shown that it is challenging to compare different compositions of floors and floating floors. In their study, a comparison of several floor types showed large SPL differences at low frequencies. Consequently, annoyance ratings for basketball bouncing lead to higher annoyance ratings compared to the other evaluated sounds (chair moving, walking with shoes and walking with socks) [41]. To summarize, the low frequencies seem to be of great importance for the perception of impact sound in lightweight buildings, while at the same time the measurement approaches in this frequency range reach a hard limit for measurement methods that could be extended to this frequency range.

Another aspect to consider is the perception of low frequencies, which are not only perceived as sound but also as whole-body vibrations. In a recent study, Dolezal et al. [54] included the reproduction of vibrations in the listening test, which could provide us with new insights into the perception of the low-frequency content of impact sound in the future.

4.3. Listening Test Environment

According to the technical specification of the ISO 12913-2 [55] standard for listening tests, binaural measurements and playback should be preferred over the multichannel approach. The rationale for this is that there is no standard technique or best practice examples for multichannel playback. However, only 5 of 13 studies used headphones for playback in their listening tests. In the other eight studies, different speaker configurations were used, from single loudspeaker and subwoofer [31] to multichannel playback setups (4.1 [46], 5.1 [35] or 8.1 [37]) and even a complete virtual studio setup [42]. It is also important to note that of the studies reviewed, only Amiryarahmadi and Kropp [42] evaluated the naturalness of the playback. Considering that systematic differences were found between the different playback methods [56], future research on realistic sound reproduction methods is of great importance.

4.4. Spectral, Spatial and Temporal Characteristics

The overview shows that the implementation of spatial and temporal features in the playback of impact sound leads to a more realistic reproduction. In Frescura et al. [45], a larger IACC led to a higher annoyance rating, which is also a parameter related to the ability to localize sound sources. Jo and Jeon [34] also found that annoyance from impact sound is rated differently when given directional information, in this case varying temporal decay rates of the sound source. Kim et al. [46] investigated the duration, number and level variation of impact sound and showed that sound energy should be taken into account. Since annoyance increased with increasing duration and number of impact sounds, the authors suggested that different impact sounds could be misanalyzed. Strong temporal variations in the impact sound samples studied also required longer listening tests, which is impractical, making a direct comparison of time varying stimuli difficult. In view of these results, temporal and spatial characteristics should be considered for an accurate subjective evaluation of impact sound.

4.5. Non-Acoustic Factors

In several studies, self-rated noise sensitivity and psychophysiological activities (heart rate, electrodermal activity or respiratory rate) were included in the evaluation, which differs from the studies examined by Vardaxis and Bard [11] in 2018, in which noise sensitivity was only examined by Jeon et al. [12] to assess cultural differences between Germans and Koreans. Thus, there has been a trend in recent years to include self-rated noise sensitivity and psychophysiological measures in the perceptual evaluation of impact sound annoyance.

In the studies by Park et al. [31] and Frescura et al. [45], the participants were divided into a group with high and a group with low noise sensitivity. In both cases, the high noise sensitivity group was associated with higher annoyance ratings. Based on these results, the inclusion of self-rated noise sensitivity appears to be an important factor that should be pursued in further studies. Indeed, this relatively simple additional question provides a useful criterion for grouping the subjects in the post-processing of the results. However, the question arises as to whether this approach is sufficient or whether more sophisticated methods should be used and whether, for example, a division into more than two groups is necessary.

Regarding psychophysiological activities, Park et al. [31] measured electrodermal activity and respiratory rate during impact sound exposure, which showed strong habituation over time. Interestingly, the type of impact sound source had no effect on the psychophysiological measurements. These results are also consistent with Kreibig [57], who published a literature review of studies on the autonomic nervous system in emotion. They come to the conclusion that the number of studies with significant results, showing annoyance affecting physiological parameters, are insufficient [57]. With regard to the influence of the sound pressure level on the psychophysiological response, a study by Park et al. from 2017 indicates that although the source of impact sound has no influence, the sound pressure level of the impact sound does. The arousal state of the participants was influenced by louder impact noises. This was shown by a deceleration in heart rate and an increase in EDA and RR [58].

Another non-acoustic factor that was investigated is the dependence of the time of day (day/night) on the perceived annoyance of impact sound. In this review, only Frescura et al. [45] dealt with this aspect. Footstep sound in a simulated night condition was rated as more annoying than in a daytime condition.

4.6. Additional Dependent Variables

In addition to the dependent variable *annoyance*, other dependent variables were also subjectively evaluated, which is meaningful because they expose alternative ways in which annoyance can be expressed. For Jo and Jeon [34], the causes of *annoyance* were described as *dissatisfaction*, *irregularity* and *discontinuity*. Amiryarahmadi and Kropp [42] used *reverberation* and *thumping* to observe changes in floor design and thus differences in perception. In the study by Frescura and Lee [32], annoyance ratings at normal and fast walking paces were surprisingly lower at 45 dB SPL than at 40 dB SPL, suggesting that sound pressure level alone cannot fully explain annoyance. Therefore, the SQ metrics of *sharpness*, *roughness* and *fluctuation strength* were also evaluated. This showed that the louder and sharper the impact sound, the higher the annoyance ratings. Hongisto et al. [41], who compared the damping efficiency of different floor coverings, also came to the conclusion that the perceived annoyance strongly depends on the type of stimuli used. This underlines the need for perceptual evaluations to improve acoustic comfort in the built environment. In this context, the study by Frescura et al. [49] stands out in particular, in which no perceptual evaluation was carried out in the form of listening tests, but rather the spectral

characteristics of an impact sound source was evaluated. In fact, the authors' conclusions are not consistent with those of the other studies.

4.7. Number of Participants

The differences in the number of listening test participants varied greatly between the individual studies. In 8 of 13 studies (Amiryarahmadi and Kropp [42], Frescura and Lee [32], Öqvist et al. [28], Trapet et al. [37], Panosso and Paul [47], Hongisto et al. [41], Park et al. [31] and Jo and Jeon [34]), the listening tests were conducted with the help of 20 to 40 participants and four studies (Jeong et al. [35], Frescura et al. [45], Kim et al. [46] and Kylliänen et al. [39]) conducted the listening tests with a number of participants between 43 and 55. Only two studies had more than 100 participants. Following the same procedure, Jeon et al. [35] conducted their listening test once with 101 participants to evaluate the damping efficiency of heavyweight buildings and once with 110 participants to evaluate lightweight buildings, while Shin et al. [44] performed their listening test with 105 participants.

In general, most studies included a relatively small number of listeners, while none provided a statistical interpretation for the choice of this number. In this regard, the results of studies with a relatively small number of participants should be considered of limited significance, while for future research it is suggested to provide more details on the statistical aspects of the studies.

4.8. Structures Investigated

Most studies provide information on the structural composition and thickness of the individual layers. Four studies [28,37,44,49] also show schematic cross-sections of the tested structures. The number of different floor compositions varies between the studies from 1 [31,34,37,45,46,46] to 2 [28,47], 4 [32,49], 6 [41], 9 [39], up to 10 [42] tested structures. Jeong et al. (2019) [35] did not specify the number of structures used. Shin et al. (2022) [44] took a different approach by deriving representative frequency spectra for each impact sound source based on frequency characteristics obtained from the measurement of 80 heavyweight and 60 lightweight buildings. In 10 studies [31,32,37,39,41,42,45–47,49], test facilities were used for sound recordings, while in 4 studies [28,34,35,44] recordings were made in residential buildings. The comparability of the study results is made even more difficult by the use of different structures and materials. In the best case scenario, standardization of the floor properties would also be advantageous in order to be able to compare the impact sound effects for structures other than those for which standardized instruments already exist. This would certainly be beneficial, at least in terms of comparable assessments of annoyance and correlation values with the descriptors.

4.9. New Findings

The similarities and differences identified are presented below in comparison with the conclusions of the literature review by Vardaxis and Bard [11]. In terms of the number of articles published on this topic, Vardaxis and Bard considered 16 studies published between 2000 and 2017. In this review, 13 studies from 2018 to 2023 were presented, which can be interpreted as an increased interest in the perceptual evaluation of impact sound given the length of the observed time window.

In the studies included in the two literature reviews, a large number of standardized and modified SNQs were evaluated (see Table A1). In general, it can be stated that most SNQs do not correlate very well for all types of impact sound sources. In particular, walking sounds (barefoot or with socks) seem to be challenging to evaluate. Kylliäinen also comes to this conclusion in his doctoral thesis [30]. He argues that these are not only strongly perceptible with heavy structures, but also with light structures and should

therefore be evaluated perceptually. He recommends further listening tests with a focus on wooden structures. In this context, the conclusion of Vardaxis and Bard [11] suggests that footstep sound can be well reproduced by an impact ball, while the results of Shin et al. [44] indicate that this is not the case and that a standardized source for walking should be further developed.

Based on the review by Vardaxis and Bard [11], standardized descriptors for the tapping machine are considered sufficient. This is also evident from the review by Trapet et al. [37], Panosso and Paul [47] and Frescura et al. [49] There also seems to be agreement that including low frequencies down to 50 Hz (or even down to 20 Hz) in the impact sound evaluation would increase the correlation to subjective annoyance from impact sound. Nevertheless, the modified spectral-matching conditions as in the study by Öqvist et al. [28] cannot be seen as a solution to the low-frequency problem. Especially with regard to the low-frequency extension of the impact sound evaluation, the measurement uncertainties need to be discussed further. In addition, the spatial and temporal characteristics (modulation, decay and other temporal characteristics) of impact sound, e.g., in the form of IACC or decay rate, were identified by Vardaxis and Bard as important for subjective evaluation and perception. The results of the studies we examined came to the same conclusion, as the reported annoyance ratings were systematically higher when spatial information was provided [34].

5. Conclusions

This literature review focuses on the relation between individual numbered descriptors of impact sound and the corresponding subjectively perceived annoyance ratings. To this end, we examined and presented 14 scientific articles found in established research databases and published between 2018 and 2023. The minimum requirement for inclusion of the studies was that listening tests were conducted under laboratory conditions and that their results were correlated with at least one SNQ. To provide an overview, each study was summarized, focusing on the test design, procedure and key outcomes. To provide a deeper insight, further details of each study are summarized in table form (see Figure A1 and Table A1). Similar topics of interest were clustered and similarities or different results were identified. A brief comparison with the 2018 literature review by Vardaxis and Bard [11] is also included.

Research has largely focused on walking stimuli (barefoot or with socks) and the application of various spectrum adaptation terms to assess the low-frequency content of impact sound. However, no general and consistent results were obtained. Regarding the listening test setup and the presentation of the stimuli, the findings of Vardaxis and Bard [11] can be acknowledged. Nevertheless, there is relevant evidence that more spatial and temporal features of the impact sound need to be considered, as these additional auditory cues improve our impact sound localization, which seems to lead to higher annoyance ratings. The additional information on self-rated noise sensitivity was also found to be relevant and should also be considered in future studies, especially as it can be easily integrated into the study.

An important question that remains open for future discussion is the definition of the dependent variables that should be evaluated and how they relate to annoyance. In addition, the differences between the structures of the floors may pose a challenge for the comparison of results in the laboratory. In this respect, extending the assessment of impact sound to lower frequencies could, according to authors, even be unachievable. In fact, due to the modal behavior that determines the response, this frequency range can generate unacceptable uncertainties for the experimental evaluation as well as the reproduction of impact sound for listening tests. On the other hand, a standardized and validated

measurement setup would be beneficial to reduce some of the reproduction uncertainties resulting from the use of the different listening setups. Overall, we can conclude, which is also in line with the conclusions of the studies included in the review, that further research activities are needed in this research area relevant for the improvement of well-being in the built environment.

Funding: The authors gratefully acknowledge the financial support from the Slovenian Research Agency (research core funding No. Z1-4388, Toward better understanding the diffuse sound field, and research core funding No. J4-3087, Engineered wood composites with enhanced impact sound insulation performance to improve human wellbeing).

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

TLA	Three letter acronym
LD	Linear dichroism
SNQ	Single number quantity
HRTF	Head-related transfer function
HMD	Head-mounted display
fEMG	Facial electromyography
EDA	Electrodermal activity
HR	Heart rate
RR	Respiration rate

Appendix A

Author	Listening Tests and Reproduction	Variables and Descriptors	Correlations and Statistical Significance
Öqvist et al. (2018) [28]	**Participants:** 24 **Recordings:** Field measurement of binaural sound signals with artificial head in: - living room in heavy hollow construction - living room in lightweight wooden construction **Playback setup:** Headphones and subwoofer	**Independent:** Walking with shoes and walking with socks in heavyweight and lightweight buildings **Dependent:** Annoyance **Descriptors:** $L_{nT,w} = L'_{nT,w}$, $L_{nT,w,50} = L'_{nT,w} + C_{I,50\text{-}2500}$, $L_{nT,w,25} = L'_{nT,w} + C_{I,25\text{-}2500}$, $L_{nT,w,20} = L'_{nT,w} + C_{I,20\text{-}2500}$, $L_{nT,w,20,AL} = L'_{nT,w+} + C_{I,Akulite,20\text{-}2500}$, $L_{nT,w,25,SS}$, $L_{nT,w,20,SS}$, $L_{nT,w,20,AL,SS}$	**Models and evaluation parameters:** Multiple regression models (ANOVA): - Listening test 1: 95% Wilson confidence intervals for the mean (wooden and concrete construction) - Listening test 2: 95% confidence interval **Results:** Positive response ratio for the wooden construction considerably higher than for concrete (for both impact noise types).

Park et al. (2018) [31]	**Participants:** 34, classified into high and low sensitivity groups
	Recordings: Road traffic (field measurement), footsteps and rubber ball (laboratory measurements)
	Playback Setup: Loudspeaker and subwoofer; additional loudspeaker with ambient noise (road traffic); playback of recorded right channel signal only to avoid spatial effects
		Independent: Footsteps, rubber ball and road traffic for high and low sensitivity group
		Dependent: Annoyance, heart rate (HR), electrodermal activity (EDA) and respiratory rate (RR)
		Descriptors:
		L_{AFmax}, $L_{Aeq,\,5min}$, L_{AE}, L_{10} and L_{90}
			Models and parameters:
			Repeated measures ANOVA
			Results:
			- Correlation coefficients between annoyance and noise level for ball = 0.78 and for real = 0.75, $p < 0.01$, respectively
			- Correlation between annoyance and sound level:
			  - for low sensitivity group: ball = 0.73, real = 0.71, $p < 0.01$
			  - for high sensitivity group: ball = 0.93, real = 0.88, $p < 0.01$

Frescura and Lee (2019) [32]	**Participants:** 20 **Recordings:** laboratory measurements on 4 configurations of lightweight timber joists floor: - 4 impact sound types: adult walking normal, adult walking (108 bpm), adult walking fast (132 bpm), kid running - 2 airborne sound types: speech, piano playing **Playback setup:** In audiometric booth with headphones and subwoofer	**Independent:** 4 impact sound types, 2 airborne sound types, 4 configurations of lightweight timber joists floor **Dependent:** Annoyance, facial electromyography (fEMG), electrodermal activity (EDA), heart rate (HR), respiration rate (RR) **Descriptors:** L_{Amax}, Loudness (SQ), Sharpness (SQ), Roughness (SQ), Fluctuation strength (SQ)	**Models and parameters:** - Multiple linear regression: $annoyance \approx a_1 loudness + a_2 sharpness$ **Results:** - Partial coefficients for $a_1 = 0.64$, and $a_2 = 0.38$, $p < 0.05$, respectively - Obtained total coefficient 0.91, $p < 0.05$

Figure A1. *Cont.*

Author	Listening Tests and Reproduction	Variables and Descriptors	Correlations and Statistical Significance
Jo and Jeon (2019) [34]	**Participants:** 40 **Recordings:** Rubber ball, walking **Playback:** 4 test environments (Mono, HRTF, HMD, HRTF and HMD) **Reproduction:** Open-type headphone and subwoofer	**Independent:** 2 impact sound types, 4 test environments, SPL, decay rate **Dependent:** Annoyance, semantic expressions (dissatisfaction, irregularity, discontinuity) **Descriptors:** L_{AFmax}, decay rate	**Models and parameters:** (2)–(5): linear relationship with annoyance (%A), (6)–(9): linear regression equations for the allowance limit (%AL) **Results:** (2) % A_{NONE} = 5.21 $L_{A,Fmax}$ − 231.37 (R^2 = 0.99, p <0.01) (3) % A_{HRTF} = 5.31 $L_{A,Fmax}$ − 200.84 (R^2 = 0.99, p <0.01) (4) % A_{HMD} = 5.91 $L_{A,Fmax}$ − 265.85 (R^2 = 0.99, p <0.01) (5) % $A_{HRTF+HMD}$ = 6.36 $L_{A,Fmax}$ − 253.21 (R^2 = 0.99, p <0.01) (6) % AL_{NONE} = −3.81 $L_{A,Fmax}$ − 276.39 (R^2 = 0.99, p <0.01) (7) % AL_{HRTF} = −4.61 $L_{A,Fmax}$ − 291.79 (R^2 = 0.99, p <0.01) (8) % AL_{HMD} = 5.01 $L_{A,Fmax}$ − 336.88 (R^2 = 0.99, p <0.01) (9) % $AL_{HRTF+HMD}$ = −5.61 $L_{A,Fmax}$ − 339.16 (R^2 = 0.99, p <0.01) - Correlation with DR insignificant (p >0.05) - Main effect of SPL and DR on annoyance significant (p >0.01)
Jeong et al. (2019) [35]	*Experiment A1:* **Participants:** 101 **Recordings:** Binaural recordings with head-and-torso simulator of rubber ball in heavyweight buildings *Experiment A2:* **Participants:** 110 **Recordings:** Binaural recordings with head-and-torso simulator of rubber ball and adult jumping in lightweight buildings *Experiment B:* **Participants:** 43 **Recordings:** Binaural recordings with head-and-torso simulator of rubber ball and adult jumping in lightweight buildings **Playback:** *Experiment A1 and 2:* 2 subwoofers in front of participant, 5 loudspeakers 1.2 m above the floor *Experiment B*: 1 loudspeaker 2 m above the floor, subwoofer behind participant	**Independent:** Impact sound types **Dependent:** Annoyance **Descriptors:** $L_{iA,Fmax}$, $L_{iA,Fmax,AW}$, $L_{iAvg,Fmax(63\text{-}500)}$, $L_{iA,Fmax,r}$, Loudness, N_{max}, N_5	**Models and parameters:** - Correlation coefficients between SNQ and annoyance ratings across impact sources **Results:** *Experiment A1 and 2*: | | Rub_H | Rub_L | Jump_L | |---|---|---|---| | $L_{iA,Fmax,AW}$ | 0.949 | 0.939 | 0.845 | | $L_{iA,Fmax,r}$ | 0.929 | 0.924 | 0.834 | | $L_{iA,Fmax}$ | 0.953 | 0.939 | 0.848 | | $L_{iAvg,Fmax(63\text{-}500)}$ | 0.963 | 0.950 | 0.849 | | Loudness | 0.947 | 0.930 | 0.905 | | N_{max} | 0.881 | 0.858 | 0.868 | | N_5 | 0.887 | 0.856 | 0.859 | *Experiment B*: | | Rub_H | Rub_L | Jump_L | |---|---|---|---| | $L_{iA,Fmax,AW}$ | 0.983 | 0.974 | 0.989 | | $L_{iA,Fmax,r}$ | 0.976 | 0.972 | 0.973 | | $L_{iA,Fmax}$ | 0.986 | 0.990 | 0.992 | | $L_{iAvg,Fmax(63\text{-}500)}$ | 0.974 | 0.965 | 0.991 | | Loudness | 0.974 | 0.987 | 0.988 | | N_{max} | 0.865 | 0.931 | 0.937 | | N_5 | 0.856 | 0.927 | 0.939 | - Rub_H: Rubber ball, heavyweight building - Rub_L: Rubber ball, lightweight building - Jump_L: Jumping, lightweight building

Figure A1. *Cont.*

Author	Listening Tests and Reproduction	Variables and Descriptors	Correlations and Statistical Significance
Kylliänen et al. (2019) [39]	**Participants:** 55 **Recordings:** S1: walking with hard shoes, S2: walking with socks, S3: walking with soft shoes, S4: super ball bouncing, S5: chair moving on 9 different floor types **Playback:** No information given	**Independent:** Impact sound types and floor types **Dependent:** Loudness, annoyance, acceptability **Descriptors:** $L'_{n,w} + C_{I,S1}$, $L'_{n,w} + C_{I,S2}$, $L'_{n,w} + C_{I,S3}$, $L'_{n,w} + C_{I,S4}$, $L'_{n,w} + C_{I,S5}$, $L'_{n,w} + C_{I,opt}$, $L'_{n,w}$, $L'_{n,w} + C_I$, $L'_{n,w} + C_{I,50\text{-}2500}$	**Models and parameters:** - Squared Pearson's correlation coefficients (r^2) of SNQs for each impact sound type (S1–S5) **Results:**

SNQ	S1	S2	S3	S4	S5
$L'_{n,w} + C_{I,S1}$	0.93	0.38	0.75	0.35	0.73
$L'_{n,w} + C_{I,S2}$	0.41	0.87	0.30	0.01	0.31
$L'_{n,w} + C_{I,S3}$	0.91	0.35	0.77	0.42	0.69
$L'_{n,w} + C_{I,S4}$	0.87	0.24	0.71	0.56	0.59
$L'_{n,w} + C_{I,S5}$	0.75	0.26	0.61	0.20	0.87
$L'_{n,w} + C_{I,opt}$	0.92	0.40	0.75	0.35	0.74
$L'_{n,w}$	0.68	0.09	0.54	0.30	0.80
$L'_{n,w} + C_I$	0.83	0.17	0.68	0.44	0.75
$L'_{n,w} + C_{I,50\text{-}2500}$	0.82	0.27	0.65	0.29	0.82

Müller-Trapet and Zeitler (2020) [37]	**Participants:** 26 **Recordings:** Tapping machine, single hammer impact from tapping machine, rubber ball from 10 cm, rubber ball from 1 m, walking with shoes, walking barefoot **Playback:** Ambisonics method with 8 loudspeakers and 3 subwoofers	**Independent:** Impact source types **Dependent:** Annoyance **Descriptors:** ICC, $L_{n,w}$, $L'_{n,w} + C_{I,50}$, $L_{AF,max}$, $L_{CF,max}$	**Models and parameters:** - Coefficient of determination (R^2): **Results:** - Ball drop from 1 m: $R^2 = 0.89$ ($L_{AF,max}$) - Ball drop from 10 cm: $R^2 = 0.94$ ($L_{n,w} + C_{I,50}$) - Single hammer taps: $R^2 = 0.87$ (ICC), $R^2 = 0.93$ ($L_{n,w}$), $R^2 = 0.95$ ($L_{n,w} + C_{I,50}$) - Walking with shoes: - Correlates with all SNQs equally well: $R^2 \approx 0.8$ - Walking barefoot: - No SNQs correlated well: $R^2 < 0.4$ - Except SNQ with C-weighting: $R^2 = 0.87$ ($L_{CF,max}$) - Highest correlation for average across all impact sources: $L_{n,w} + C_{I,50} = 0.76$
Hongisto et al. (2020) [41]	**Participants:** 30 **Recordings:** 4 natural impact sound types (basketball bouncing, chair moving, walking with shoes, walking with socks) on 6 floor types (4 floating floors, 2 non-floating floors) in standardized impact sound laboratory **Playback:** Headphones	**Independent:** Floor types and sound types **Dependent:** Annoyance **Descriptors:** $L_{n,w}$, $L_{n,w} + C_I$, $L_{n,w} + C_{I,50}$, $L_{iA,Fmax}$, ΔL_w, ΔL_{lin}	**Models and parameters:** - Spearman's rank correlation coefficient p between objective and subjective rank orders of six floor types. Aggregate rank order (ARO) is based on sum of subjective rank orders over four sound types. **Results:**

	$L_{n,w}$	$L_{n,w} + C_I$	$L_{n,w} + C_{I,50}$	ΔL_w	ΔL_{lin}	$L_{iA,Fmax}$
S^1	0.39	0.39	0.49	0.49	0.39	0.39
S^2	0.63	0.86 *	0.89 *	0.82 *	0.94 **	0.94 **
S^3	0.89 *	0.89 *	0.91 *	0.93 **	0.89 *	0.89 *
S^4	−0.27	−0.27	−0.54	0.42 *	−0.40	−0.40
ARO	0.75	0.93 **	0.97 **	0.91*	0.94 **	0.94 **

The coefficient is statistically significant, if it is signed with an asterisk (* $p < 0.05$; $p <$ ** < 0.01).

Figure A1. *Cont.*

Author	Listening Tests and Reproduction	Variables and Descriptors	Correlations and Statistical Significance
Amiryarahmadi and Kropp (2021) [42]	**Participants:** 20 **Recordings:** Footsteps on 11, mostly lightweight, floor types **Playback:** Virtual design studio with invisible loudspeaker grid	**Independent:** Footsteps **Dependent:** Loudness, distinctness, thumping, reverberation, annoyance, naturalness **Descriptors:** $L'_{n,w}$, $L'_{n,w} + C_{I,50\text{-}2500}$, $L'_{n,w} + C_{I,20\text{-}2500}$	**Models and parameters:** - Linear regression model - Coefficients of determination of R^2 and statistical significance probability values (p-values) **Results:** Loudness: $L'_{n,w}$: $R^2 = 0.77$, p = 0.0003 - $L'_{n,w} + C_{I,50\text{-}2500}$: $R^2 = 0.35$, $p = 0.06$ - $L'_{n,w} + C_{I,20\text{-}2500}$: $R^2 = 0.39$, $p = 0.04$ Annoyance: - $L'_{n,w}$: $R^2 = 0.53$, $p = 0.009$ - $L'_{n,w} + C_{I,50\text{-}2500}$: $R^2 = 0.27$, $p = 0.1$ - $L'_{n,w} + C_{I,20\text{-}2500}$: $R^2 = 0.45$, $p = 0.02$
Shin et al. (2021) [44]	**Participants:** 105 **Recordings:** Tire, rubber ball, walking and running in apartment buildings with 180 mm slab thickness **Playback:** 2 loudspeakers (left, right) and one subwoofer in front of 4 participants tested simultaneously	**Independent:** Impact sound types **Dependent:** Annoyance **Descriptors:** $L_{iA,Fmax}$ for tire and rubber ball, $L_{A,Fmax}$ for walking and running	**Models and parameters:** - **Results:** - Significant effect on the annoyance ratings was found depending on the spectrum type using a repeated measures ANOVA for both tire and rubber ball. - No correlation values given
Frescura et al. (2022) [45]	**Participants:** 46, divided into low and high noise sensitivity groups **Recordings:** 3 footstep sounds (walking in a figure-of-eight, walking along a straight line, walking on three spots) of 2 individual walkers at two different paces (normal: 1.8 s^{-1} and very slow pace: 1 s^{-1}) in acoustic laboratory on lightweight timber joist floor sample recorded with binaural head **Playback:** Ambisonics method with 8 loudspeakers, 4 at upper and 4 at lower corners of building acoustics laboratory	**Independent:** Walking **Dependent:** Annoyance, noise sensitivity, attitude towards neighbors, chronotype **Descriptors:** IACC, L_{AFmax}	**Models and parameters:** - Multiple linear regression: annoyance ≈ f(IACC) + f(SPL) ≈ a(IACC) + b(SPL) - Pearson's correlation coefficient between annoyance and physical properties of sound stimuli (IACC, L_{AFmax}) **Results:** - Standardized partial regression coefficients: 0.135 (IACC), 0.376 (SPL), $p < 0$, respectively - Coefficient of determination: $R^2 = 0.231$ - IACC significant effect on annoyance ratings: - Correlation coefficient between annoyance and IACC: r = 0.332, $p < 0.01$ - For both paces annoyance significantly correlated with IACC: r = 0.328 for normal and r = 0.332 for very slow pace, $p < 0.01$, respectively - Significant correlation with annoyance in daytime: r = 0.346, $p < 0.01$ and nighttime (r = 0.319, $p < 0.01$) - SPL significant effect on annoyance ratings: - Correlation coefficient between annoyance and SPL: r = 0.421,$p < 0.01$ - For both paces annoyance significantly correlated with SPL: r = 0.468 for normal and r = 0.328 for very slow pace, $p < 0.01$, respectively
Kim et al. (2022) [46]	**Participants:** 54 **Recordings:** Children's jumping in test building **Playback:** 4.1 channel loudspeaker configuration in 1.8 m height at four corners and subwoofer	**Independent:** Children's jumping (SIS: single impact stimuli, MIS: multi-impact stimuli) **Dependent:** Annoyance **Descriptors:** $L_{iA,Fmax}$, L_{Aeq}, L_{AE}	**Models and parameters:** - Coefficients of determination **Results:** - Annoyance to MIS: $R^2 = 0.7242$ (L_{Aeq}), $R^2 = 0.7314$ (L_{AE}) - Annoyance to SIS: no data given - Both SNQs higher exploratory power than $L_{iA,Fmax}$

Figure A1. *Cont.*

Author	Listening Tests and Reproduction	Variables and Descriptors	Correlations and Statistical Significance
Panosso and Paul (2022) [47]	**Participants:** 29 **Recordings:** Tapping machine and calibrated tire in acoustic test studio with binaural-head-and-torso simulator **Playback:** Headphones	**Independent:** Tapping machine and calibrated tire on wood laminate flooring and porcelain tile flooring **Dependent:** Noise annoyance and loudness sensation **Descriptors:** $L'_{nT,w}$, $L_{n100\text{-}3150Hz}$, $L_{i,Favg,Fmax}$, $L_{i,Fmax,50\text{-}630Hz}$, $L_{AF,5\%}$, $L_{AF,10\%}$	**Models and parameters:** - Linear regression and Pearson's coefficient calculation **Results:** Pearson's correlation coefficient for subjective and objective variables R^2 obtained in the linear regression analysis correlating subjective and objective ratings NA: noise annoyance, LS: loudness sensation, G1–4: Groups, nv: negligible value Group 1: tapping machine and porcelain tile, Group 2: tapping machine and wood laminate, Group 3: calibrated tire and porcelain tile, Group 4: calibrated tire and wood laminate

	$L'_{nT,w}$	$L_{n100\text{-}3150Hz}$	$L_{i,Favg,Fmax}$	$L_{i,Fmax,50\text{-}630Hz}$	$L_{AF,5\%}$	$L_{AF,10\%}$
NA G1	0.92	0.93	-	-	-	-
LS G1	0.90	0.91	-	-	-	-
NA G2	0.85	0.86	-	-	-	-
LS G2	0.75	0.75	-	-	-	-
NA G3	-	0 -	0.89	0.86	0.76	0.66
LS G3	-	0 -	0.86	0.81	0.88	0.83
NA G4	-	-	0.11	nv	0.24	0.34
LS G4	-	-	0.38	0.37	0.71	0.76

	$L'_{nT,w}$	$L_{n100\text{-}3150Hz}$	$L_{i,Favg,Fmax}$	$L_{i,Fmax,50\text{-}630Hz}$	$L_{AF,5\%}$	$L_{AF,10\%}$
NA G1	0.86	0.87	-	-	-	-
LS G1	0.81	0.83	-	-	-	-
NA G2	0.72	0.74	-	-	-	-
LS G2	0.56	0.56	-	-	-	-
NA G3	-	-	0.79	0.73	0.58	0.44
LS G3	-	-	0.74	0.66	0.77	0.69
NA G4	-	-	0.01	nv	0.06	0.12
LS G4	-	-	0.14	0.14	0.50	0.58

Figure A1. *Cont.*

Author	Listening Tests and Reproduction	Variables and Descriptors	Correlations and Statistical Significance
Frescura et al. (2021) [49]	Study did not conduct listening tests **Recordings:** Laboratory	**Impact sound types:** 2 standardized (tapping machine, rubber ball), 3 footstep sources (adult walking, child running, child jumping) and 3 dropped objects (0.5 L bottle from 1 m, 5 kg sand bag from 0.5 m, box of wooden blocks from 1 m) **Descriptors:** a) For standardized tapping machine: $L_{n,w}$, $L'_{n,w} + C_I$, $L'_{n,w} + C_{I(50\text{-}2500)}$, $L'_{n,Aw}$ b) For standardized impact ball: $L'_{i,Fmax,AW}$, $L'_{i,Fmax,r}$, $L'_{i,Fmax,(63\text{-}500Hz)}$ **Noise ratings:** L_{Aeq}, L_{AFmax}, L_N	**Models and parameters:** - Correlations coefficients between standardized and real impact sound sources in wooden lightweight structures **Results:**

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

(* $p < 0.05$ and ** $p < 0.01$)

Figure A1. The table summarizes the most important content for each study discussed. In chronological order, after the reference in the previous column, the test and reproduction environment are given (column 2), the dependent, independent and SNQs used are listed (column 3) and the main results are summarized. Column 2 lists the number of participants, the description of the stimuli and the devices used for reproduction. Column 3 lists all variables and descriptors used for the subsequent statistical analysis. The last column summarizes the statistical models used and the main findings.

Table A1. The SNQs used in the studies examined with their definitions and the corresponding references.

SNQ	Definition	Standard	References
IACC	Interaural cross-correlation function: Covariance of delayed versions of the left and right ear time signal	ISO 3382-1	[49]
SPL	Sound pressure level	ISO 3740:2019	[34]
ΔL_w	Weighted reduction of ISPL	ISO 717-2	[41]
ΔL_{lin}	Weighted reduction of ISPL + spectrum adaptation term C_Δ	ISO 717-2	[41]
ICC	Derived from sound attenuation values tested at sixteen standard frequencies from 100 to 3150 Hz		[37]
L_{10}	Percentile sound pressure level		[31]
L_{90}	Percentile sound pressure level		[31]
L_A	A-weighted sound pressure level		
L_{AE}	A-weighted sound pressure level		[31,46]
$L_{AF,5\%}$	Corresponding to the A-weighted SPL exceeded in 5% of the measurement time		[47]
$L_{AF,10\%}$	Corresponding to the A-weighted SPL exceeded in 10% of the measurement time		[47]
L_{Aeq}	A-weighted sound pressure level in dB, equivalent to the total sound energy over a specific period of time	JIS A 1418, KS F 2810-2	[31,46,49]
L_{Amax}	Maximum A-weighted sound pressure level	JIS A 1418, KS F 2810-2	[32]
$L_{A,Fmax}$	A-weighted, maximum sound level measured with a fast time-constant		[31,34,37,46,49]
$L_{Amax,r}$		JIS A 14119-2, KS F KS 2863-2	
$L_{iA,Fmax}$	A-weighted maximum impact sound level		[35,41,44,46]

Table A1. *Cont.*

SNQ	Definition	Standard	References
$L_{LiA,Fmax,AW}$			[35]
$L_{Li,Fmax,AW}$	Inverse A-weighted impact sound pressure level	JIS A 1418, KS F 2810-2	[49]
$L_{i,Fmax,r}$	A-weighted impact sound pressure level		[49]
$L_{i,Fmax(50\text{-}630\,Hz)}$			[47]
$L_{iA,Fmax,r}$			[35]
$L_{iAvg,Fmax(63\text{-}500\,Hz)}$	Arithmetic average of maximum sound pressure levels in octave bands from 63 Hz to 500 Hz	JIS A 14119-2, KS F 2863-2	[35,49]
$L_{i,Favg,Fmax}$			[47]
DR	Similar to reverberation time but for impact sounds		[34]
JND	Just noticeable difference		
$L_{n,AW}$		JIS A 14119-2, KS F 2863-1	[49]
$L_{n,w}$	Impact sound insulation index characterizing a building element (laboratory measurements)	ISO 717-2, ISO 140-7, EN ISO 12354-2, ISO 16283-2	[28,37,41,49]
$L'_{n,w}$	Apparent impact sound insulation index (same as $L_{n,w}$ for field measurements)	ISO 717-2, ISO 140-7, EN ISO 12354-2, ISO 16283-2	[39,42]
$L_{nT,w}$	Weighted standardized impact sound pressure level—laboratory measurements	ISO 140-7	[28]
$L'_{nT,w}$	Weighted standardized impact sound pressure level—field measurements	ISO 717-2	[28,42,47]
$L'_{n100\text{-}3150\,Hz}$			
$L_{CF,max}$	C-weighted, fast response, maximum, sound level		[37]

Table A1. *Cont.*

SNQ	Definition	Standard	References
$L_{nT,w,25,SS}$			[28]
$L_{nT,w,20,SS}$			[28]
$L_{nT,w,20,AL,SS}$			[28]
$L'_{n100\text{-}3150\,Hz}$			[47]
Spectrum adaptation terms	**Definition**	**Standard**	**References**
C	C is an A-weighted pink noise spectrum adaptation term	ISO 717-1, ISO 717-2, EN ISO 12354-1, EN ISO 12354-2	
C_I	Unweighted impact sound level	ISO 71-2	[39,41,49]
$C_{I,50}$			[37,41]
C_{50}			
$C_{I,20\text{-}2500\,Hz}$	Unweighted impact sound level for the frequency range 20–2500Ḣz	SS 25267:2015	[28,42]
$C_{I,Akulite,20\text{-}2500}$			[28]
$C_{I,25\text{-}2500\,Hz}$	Unweighted impact sound level for the frequency range 25–2500Ḣz		[28]
$C_{I,50\text{-}2500\,Hz}$	Unweighted impact sound level for the frequency range 50–2500Ḣz	ISO 717-2	[28,39,42,49]
$C_{I,S1} \ldots C_{I,S5}$			[39]
$C_{I,opt}$			[39]
C_Δ			[41]
Sound Quality	**Definition**	**Standard**	**References**
L	Loudness: sound quality metric defined by Zwicker and Fastl	ISO 532-1:2017	[32,35,49]
LL_Z	Zwicker's loudness level	ISO 532-1:2017	[32,35,49]

Table A1. *Cont.*

Sound Quality	Definition	Standard	References
N_5	Percentile loudness: SQ metric defined by Zwicker and Fastl	ISO 532-1:2017	[35]
N_{10}	Percentile loudness: SQ metric defined by Zwicker and Fastl	ISO 532-1:2017	[35]
N_{max}	Maximum loudness: SQ metric defined by Zwicker and Fastl	ISO 532-1:2017	[35]
FS	Fluctuation strength: SQ defined by Zwicker and Fastl		[32]
T	Tonality: SQ metric defined by Zwicker and Fastl		
UA	Unbiased annoyance: SQ metric defined by Zwicker and Fastl		
S	Sharpness: SQ metric defined by Zwicker and Fastl		[32]
R	Roughness: SQ metric defined by Zwicker and Fastl		[32]

References

1. World Health Organization. Regional Office for Europe. *Environmental Noise Guidelines for the European Region*. Available online: https://www.who.int/europe/publications/i/item/9789289053563 (accessed on 12 December 2023).
2. Langdon, F.; Buller, I.; Scholes, W. Noise from neighbours and the sound insulation of party floors and walls in flats. *J. Sound Vib.* **1983**, *88*, 243–270. [CrossRef]
3. Sato, H.; Hirota, T.; Hiramitsu, A.; Tanaka, M. Subjective evaluation of floor impact sound of wood-frame construction dwellings in different living situation. In Proceedings of the INTERNOISE 2014—43rd International Congress on Noise Control Engineering: Improving the World Through Noise Control, Melbourne, Australia, 16–19 November 2014.
4. Bard Hagberg, K. Management of Acoustics in Lightweight Structures. Ph.D. Thesis, Department of Construction Sciences, Lund University, Lund, Sweden, 2018.
5. Rasmussen, B.; Machímbarrena, M. *Building Acoustics Throughout Europe Volume 1: Towards a Common Framework in Building Acoustics Throughout Europe*; COST: Brussels, Belgium, 2014.
6. Rasmussen, B.; Rindel, J. Concepts for evaluation of sound insulation of dwellings—From chaos to consensus? In Proceedings of the Forum Acusticum Budapest 2005: 4th European Congress on Acustics, Budapest, Hungary, 29 August–2 September 2005.
7. Rasmussen, B. Acoustic classification of dwellings—A growing diversity of sound insulation descriptors in national schemes in Europe. In Proceedings of the ICA 2022 24th International Congress on Acoustics, Aalborg, Denmark, 24 October 2022; pp. 199–206.
8. *ISO-717-2:2013*; Acoustics—Rating of Sound Insulation Buildings and of Building Elements–Part 2: Impact Sound Insulation. International Organisation for Standardization: Geneva, Switzerland, 2017.
9. Lokki, T. Sensory evaluation of concert hall acoustics. In *Proceedings of Meetings on Acoustics, Montreal, QC, Canada, 2–7 June 2013*; AIP Publishing: Melville, NY, USA, 2013; Volume 19.
10. Fenech, B.; Lavia, L.; Rodgers, G.; Notley, H. Development of a new ISO Technical Specification on non-acoustic factors to improve the interpretation of socio-acoustic surveys. *Acoust. Bull.* **2022**, *48*, 54–61.
11. Vardaxis, N.G.; Bard, D. Review of acoustic comfort evaluation in dwellings: Part II—Impact sound data associated with subjective responses in laboratory tests. *Build. Acoust.* **2018**, *25*, 171–192. [CrossRef]
12. Jeon, J.Y.; Jeong, J.; Vorlaender, M.; Thaden, R. Evaluation of Floor Impact Sound Insulation in Reinforced Concrete Buildings. *Acta Acust. United Acust.* **2004**, *90*, 313–318.
13. Jeon, J.Y. Subjective Evaluation of Floor Impact Noise Based on the Model of ACF/IACF. *J. Sound Vib.* **2001**, *241*, 147–155. [CrossRef]
14. Jeon, J.Y.; Jeong, J.; Ando, Y. Objective and Subjective Evaluation of Floor Impact Noise. *J. Temporal Des. Archit. Environ.* **2008**, *2*, 20.
15. Jeon, J.Y.; Ryu, J.; Jeong, J.; Tachibana, H. Review of the Impact Ball in Evaluating Floor Impact Sound. *Acta Acust. United Acust.* **2006**, *92*, 777–786.
16. Jeon, J.Y.; Sato, S.I. Annoyance caused by heavyweight floor impact sounds in relation to the autocorrelation function and sound quality metrics. *J. Sound Vib.* **2008**, *311*, 767–785. [CrossRef]
17. Jeon, J.Y.; Lee, P.; Kim, J.; Yoo, S.Y. Subjective evaluation of heavy-weight floor impact sounds in relation to spatial characteristics. *J. Acoust. Soc. Am.* **2009**, *125*, 2987–2994. [CrossRef]
18. Kim, J.; Ryu, J.; Jeon, J.Y. Effect of temporal decay on perception of heavy-weight floor impact sounds. *J. Acoust. Soc. Am.* **2013**, *134*, 2730–2738. [CrossRef]
19. Jeon, J.Y.; Oh, S.M. Psychoacoustical evaluation of heavyweight floor impact sounds in apartment buildings. In Proceedings of the INTERNOISE 2014—43rd International Congress on Noise Control Engineering: Improving the World Through Noise Control, Melbourne, Australia, 16–19 November 2014.
20. Ryu, J.; Sato, H.; Kurakata, K.; Hiramitsu, A.; Tanaka, M.; Hirota, T. Relation between annoyance and single-number quantities for rating heavy-weight floor impact sound insulation in wooden houses. *J. Acoust. Soc. Am.* **2011**, *129*, 3047–55. [CrossRef] [PubMed]
21. Gover, B.; Bradley, J.; Schoenwald, S.; Zeitler, B. Subjective ranking of footstep and low-frequency impact sounds on lightweight wood-framed floor assemblies. In Proceedings of the Forum Acusticum, Aalborg, Denmark, 27 June–1 July 2011; pp. 1–6.
22. Bradley, J.; Zeitler, B.; Schoenwald, S. Objective and subjective assessment of lightweight wood-framed floor assemblies in response to footstep and low-frequency impact sounds. In Proceedings of the Inter-Noise, Osaka, Japan, 4–7 September 2011; Volume 3, pp. 1–7.
23. Subjective and objective evaluation of impact noise sources in wooden buildings. *Build. Acoust.* **2013**, *20*, 193–213. [CrossRef]
24. Kylliäinen, M.; Hongisto, V.; Oliva, D.; Rekola, L. A laboratory listening experiment on subjective and objective rating of impact sound insulation of concrete floors. In Proceedings of the INTER-NOISE and NOISE-CON Congress and Conference Proceedings, Hamburg, Germany, 21–24 August 2016.
25. Kylliäinen, M.; Hongisto, V.; Oliva, D.; Rekola, L. Subjective and Objective Rating of Impact Sound Insulation of a Concrete Floor with Various Coverings. *Acta Acust. United Acust.* **2017**, *103*, 236–251. [CrossRef]

26. Öqvist, R.; Ljunggren, F.; Johnsson, R. Listening test of walking noise from 20 Hz in dwellings. In Proceedings of the INTER-NOISE and NOISE-CON Congress and Conference Proceedings, Hong Kong, China, 27–30 August 2017.
27. Moher, D.; Liberati, A.; Tetzlaff, J.; Altman, D.G. Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. *BMJ* **2009**, *339*.
28. Öqvist, R.; Ljunggren, F.; Johnsson, R. Walking sound annoyance vs. impact sound insulation from 20 Hz. *Appl. Acoust.* **2018**, *135*, 1–7. [CrossRef]
29. Ljunggren, F.; Simmons, C.; Hagberg, K. Correlation between sound insulation and occupants' perception – Proposal of alternative single number rating of impact sound. *Appl. Acoust.* **2014**, *85*, 57–68. [CrossRef]
30. Kylliäinen, M. Rating the Impact Sound Insulation of Concrete Floors with Single-Number Quantities Based on a Psychoacoustic Experiment. Ph.D Thesis, Tampere University, Tampere, Finland, 2019.
31. Park, S.H.; Lee, P.J.; Jeong, J.H. Effects of Noise Sensitivity on Psychophysiological Responses to Building Noise. *Build. Environ.* **2018**, *136*, 302–311. [CrossRef]
32. Frescura, A.; Lee, P. Perception of combined indoor noise sources in lightweight buildings. In Proceedings of the International Congress on Acoustics, Aachen, Germany, 9–13 September 2019.
33. Schütte, M.; Marks, A.; Wenning, E.; Griefahn, B. The development of the noise sensitivity questionnaire. *Noise Health* **2007**, *9*, 15–24. [CrossRef]
34. Jo, H.I.; Jeon, J.Y. Downstairs Resident Classification Characteristics for Upstairs Walking Vibration Noise in an Apartment Building under Virtual Reality Environment. *Build. Environ.* **2019**, *150*, 21–32. [CrossRef]
35. Jeong, J.H.; Park, S.H.; Lee, P.J. Single-Number Quantities of Heavyweight Impact Sound Insulation. *Acta Acust. United Acust.* **2019**, *105*, 5–8. [CrossRef]
36. *ISO-16283-2:2020*; Acoustics—Field Measurements of Sound Insulation in Buildings and of Building Elements–Part 2: Impact Sound Insulation. International Organisation for Standardization: Geneva, Switzerland, 2020.
37. Müller-Trapet, M.; Möller, K.; Choi, Y.J.; Zeitler, B. A subjective study of source types and rating methods for impact sounds in buildings. In *INTER-NOISE and NOISE-CON Congress and Conference Proceedings*; Institute of Noise Control Engineering: Wakefield, MA, USA, 2020.
38. *ISO-532:2017*; Acoustics—Methods for Calculating Loudness–Part 1: Zwicker Method. International Organisation for Standardization: Geneva, Switzerland, 2017.
39. Kylliäinen, M.; Virjonen, P.; Hongisto, V. Optimized Reference Spectrum for Rating the Impact Sound Insulation of Concrete Floors. *J. Acoust. Soc. Am.* **2019**, *145*, 407–416. [CrossRef] [PubMed]
40. American Society for Testing Materials. *Standard Classification for Determination of Signle Number Metrics for Impact Noise*; ASTM International: West Conshohocken, PA, USA, 2021.
41. Hongisto, V.; Virjonen, P.; Maula, H.; Saarinen, P.; Radun, J. Impact Sound Insulation of Floating Floors: A Psychoacoustic Experiment Linking Standard Objective Rating and Subjective Perception. *Build. Environ.* **2020**, *184*, 107225. [CrossRef]
42. Amiryarahmadi, N.; Kropp, W. A virtual design studio for low frequency impact sound from walking. *Acta Acust.* **2021**, *5*, 40. [CrossRef]
43. Hagberg, K.; Larsson, K.; Bard, D. AkuLite—A research project to strengthen light weight structures. In Proceedings of the 39th International Congress on Noise Control Engineering 2010, INTER-NOISE 2010, Lisbon, Portugal, 13–16 June 2010; pp. 6032–6040.
44. Shin, H.K.; Park, S.H.; Kim, M.J.; woo Kim, K. A study on subjective response to heavy-weight impact sound through representative spectrum analysis: A case study in South Korea. *Appl. Acoust.* **2022**, *188*, 108562. [CrossRef]
45. Frescura, A.; Lee, P.J.; Soeta, Y.; Ariki, A. Effects of Spatial Characteristics of Footsteps Sounds and Non-Acoustic Factors on Annoyance in Lightweight Timber Buildings. *Build. Environ.* **2022**, *222*, 109405. [CrossRef]
46. Kim, S.; Kim, J.; Lee, S.; Song, H.; Song, M.; Ryu, J. Effect of Temporal Pattern of Impact Sound on Annoyance: Children's Impact Sounds on the Floor. *Build. Environ.* **2022**, *208*, 108609. [CrossRef]
47. Panosso, A.D.S.; Paul, S. Subjective Evaluation of Floor Impact Noise Using the Tapping Machine and a Non-Standardized Source. *Acta Sci. Technol.* **2022**, *44*, e59025. [CrossRef]
48. Otto, N.; Amman, S.; Eaton, C.; Lake, S. Guidelines for Jury Evaluations of Automotive Sounds. *J. Sound Vib.* **2001**, *35*, 24–47. [CrossRef]
49. Frescura, A.; Lee, P.J.; Schöpfer, F.; Schanda, U. Correlations between Standardised and Real Impact Sound Sources in Lightweight Wooden Structures. *Appl. Acoust.* **2021**, *173*, 107690. [CrossRef]
50. Lee, P.J.; Kim, J.H.; Jeon, J.Y. Psychoacoustical Characteristics of Impact Ball Sounds on Concrete Floors. *Acta Acust. United Acust.* **2009**, *95*, 707–717. [CrossRef]
51. Swedish Institute for Standards. *SS 25267:2015*; Acoustics—Sound Classification of Spaces in Buildings—Dwellings. Swedish Institute for Standards: Stockholm, Sweden, 2015.

52. Larsson, K.; Forssén, J.; Kropp, W.; Brunskog, J.; Ljunggren, S.; Bard, D.; Sandberg, G.; Ljunggren, F.; Ågren, A.; Hallström, O.; et al. Acoustics in Wooden Buildings–State of the Art 2008 Summary of a Swedish Cooperation Project. In Proceedings of the Joint Baltic-Nordic Acoustics Meeting, Reykjavik, Iceland, 17–19 August 2008; pp. 17–19.
53. Reynders, E.P.; Hoorickx, C.V. Uncertainty quantification of diffuse sound insulation values. *J. Sound Vib.* **2023**, *544*, 117404. [CrossRef]
54. Dolezal, F.; Reichenauer, A.; Wilfling, A.; Neusser, M.; Prislan, R. Recording, Processing, and Reproduction of Vibrations Produced by Impact Noise Sources in Buildings. *Acoustics* **2024**, *6*, 97–113. [CrossRef]
55. International Organisation for Standardization. *Acoustics—Soundscape–Part 2: Data Collection and Reporting Requirements*; International Organisation for Standardization: Geneva, Switzerland, 2018.
56. Skoda, S.; Müller-Trapet, M.; Choi, Y.J.; Cunha, I.B.D.; Mahn, J. *Annoyance Evaluation of Impact Sounds on Timber Floors in Different Listening Test*; p. 8.
57. Kreibig, S. Autonomic Nervous System Activity in Emotion: A Review. *Biol. Psychol.* **2010**, *84*, 394–421. [CrossRef] [PubMed]
58. Park, S.H.; Lee, P. Effects of floor impact noise on people—Annoyance and physiological responses. In Proceedings of the 12th ICBEN Congress on Noise as a Public Health Problem, Zurich, Switzerland, 18–22 June 2017.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.