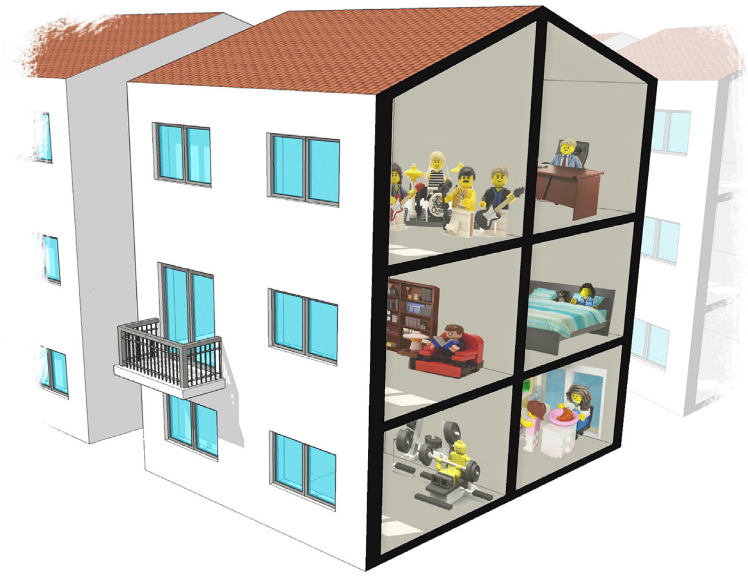


EVALUATION OF ACOUSTIC COMFORT IN APARTMENT BUILDINGS

NIKOLAOS GEORGIOS VARDAXIS

Engineering Acoustics

Doctoral Thesis

DEPARTMENT OF CONSTRUCTION SCIENCES

DIVISION OF ENGINEERING ACOUSTICS

ISRN LUTVDG/TVBA--19/1016--SE (1-220) | ISSN 0281-8477

ISBN 978-91-7895-222-9 (print) | ISBN 978-91-7895-221-2 (pdf)

DOCTORAL THESIS

EVALUATION OF ACOUSTIC COMFORT IN APARTMENT BUILDINGS

NIKOLAOS GEORGIOS VARDAXIS

Printed by Media-Tryck LU, Lund, Sweden, August 2019 *(Pl).*

For information, address:

Div. of Engineering Acoustics, Faculty of Engineering LTH,
Lund University, Box 118, SE-221 00 Lund, Sweden.

Homepage: http://www.akustik.lth.se

Acknowledgements

The present thesis project was conducted between April 2015 and September 2019 at Lund University, LTH, Department of Construction Sciences, Division of Technical Acoustics. Dr. Delphine Bard is the main supervisor and project leader. There was financial support for this research provided by Saint-Gobain Weber. The author highly appreciates the funding and would like to thank every external partner from Saint-Gobain Research (Paris, France) and Saint-Gobain Nordic Delegation (Copenhagen, Denmark) for their contribution and overall collaboration in order to realize this project.

My deepest gratitude goes to Delphine Bard, for her supervision and management during this project, for her efforts, the inspiration and the solid support at the good and bad moments of this very interesting, adventurous but also complicated and cumbersome research – that was a hell of a ride!

Great appreciation goes to my co-supervisor Susanne Heyden, who offered indispensable guidance for the setup and formulation of this thesis, for her insights and assistance during the long writing process.

I would like to give special credits to Kerstin Persson Waye, who was a co-supervisor during the first years of the project. She offered invaluable advice in order to setup the survey and define the research questions.

Further appreciation goes to my fellows in the Division of Technical Acoustics for their collaboration all these years and for various contributions and assistance with special issues during my PhD project.

Thank you dear colleagues, for the past four years in the department, for the coexistence, the help and the knowledge we exchanged.

Last but not least, I would like to express my gratitude to my family, parents and sister, for their unconditional love, encouragement and understanding during the big struggles of my (academic) life. Nothing would be the same without their support.

Abstract

This thesis concerns assessment of acoustic comfort in apartment buildings. A new approach is followed, beyond noise annoyance investigation, which was the typical path so far. The latter involved acoustic descriptors, which characterize the structural components, being associated to self-reported noise annoyance.

A socio-acoustic survey was conducted in 34 Swedish and Danish structures including 101 building units. Using a questionnaire, various parameters relevant to acoustic comfort were explored such as the living conditions, residents' emotional reactions to the sound environment, personal data and other non-acoustic parameters, as well as self-reported annoyance due to various noise sources. Building and acoustic data were also collected to test their effect on the responses.

Firstly, a noise annoyance assessment took place. Dose-response relationships were established for the resident's annoyance, dependent on acoustic descriptors, due to airborne or impact sound. The latter was the biggest disturbance, especially impact noise types (walking, thuds) from neighbors on the floor above. The number of flats in a building was found to be an additional predictor for annoyance, regarding airborne and impact sound annoyance. The same applies to the size of flats only for airborne sound annoyance. The effect of extended low frequencies in acoustic descriptors for annoyance prediction was found negligible.

Furthermore, acoustic comfort was assessed using the circumplex model of affect, a psychological tool for emotional evaluation of subjects. Two underlying dimensions for comfort were identified: pleasantness and activation. The impact sound descriptor $L'_{nT,w,100}$ predicted best pleasantness while the number of flats per building predicted best activation. A novel indicator was developed based on the pleasantness model, suggesting a measure for acoustic comfort entitled AC_{index}. Finally, based on the new indicator, 4 classes of acoustic comfort were proposed as "Very good", "Good", "Acceptable" and "No acoustic comfort", which are entitled AC-1, AC-2, AC-3 and AC-4 respectively.

Summing up, a new approach with novel results are presented in this thesis for assessment of acoustic comfort in apartments. A simple new comfort descriptor and a relevant classification system for comfort are suggested as a tool for engineers, acousticians, designers and apartment occupants.

Popular Summary

Multistory buildings are popular housing structures, since they can offer accommodation to multiple tenants. The indoor acoustic conditions of dwellings are always important and complaints arise often about noise or other issues regarding the sound environment. Noise annoyance is a common problem in housing, especially in apartment buildings and can lead to serious disturbances or even health damage. Noise is defined as the unwanted sounds, depending on the occasion, and can be produced by various sources and propagate in multiple ways between apartments. Noise from neighbors has been reported in previous studies as the biggest indoors annoyance, specifically impact noise types like footsteps with bare foot and heels or kids jumping on the floor. Moreover, acoustic comfort is a broader concept described by qualities such as: desired sounds and absence of noise, opportunities for acoustic related activities with supportive acoustic conditions and without annoying others around.

The thesis work concerns a new approach to investigate acoustic comfort in apartments, beyond noise annoyance. In the presented study, various parameters relevant to acoustic comfort are explored such as structure information, living conditions, residents' perception and emotional reactions to the sound environment, personal data and other non-acoustic parameters, as well as self-reported annoyance. A novel descriptor for acoustic comfort are developed and presented in the results, alongside a new classification system.

Specifically, a wide survey took place in 34 different structures in Sweden and Denmark (101 building units) during which building data and standardized acoustic measurements were collected. Then, a questionnaire was sent to a sum of 1941 apartments, inviting the residents to participate in the research. The participants were asked questions designed for assessment of living conditions and noise annoyance, for characterization and for emotional responses to their home's acoustic climate. Finally, 375 valid observations were gathered, analyzed and used for evaluation of acoustic comfort in dwellings.

The collected data were used to assess how people perceive their living sound environment and how they feel about acoustic conditions at home. The evaluation demonstrated a very good sense of acoustic comfort for the residents in the survey. This is probably due to the strict minimum acoustic conditions in most of the test structures set by Boverket, the Swedish National Board of Housing. Furthermore, statistical analyses were applied to acquire numerical models of noise annoyance and acoustic comfort prediction. Those models are based on the self-reported noise annoyance, evaluation of the home acoustic climate and living conditions. The models consider also construction parameters such as: type of structure, size of house and number of flats in a building unit.

Novel results are presented in this thesis for measurement and evaluation of acoustic comfort in apartments. A new descriptor was developed for that reason, utilizing the outcome of the questionnaire responses. It is a single value that could be used handily to assess acoustic comfort in housing. The descriptor corresponds to a new scale for rating acoustic comfort in apartments and a new classification system based on that. Four classes of acoustic comfort are also suggested as: “Very good”, “Good”, “Acceptable” and “No acoustic comfort”.

Summing up, this thesis sets a fundament for acoustic comfort assessment in dwellings with a novel approach and suggestions for new tools: a new indicator and classification system to characterize acoustic comfort in a house. Those new tools can be further evolved and be used by acousticians, designers, engineers, the owners or the occupants of apartments. They can also be integrated in the planning stage, before construction, to ensure a better acoustic environment in housing.

Table of Contents

Part II – Research publications and attachments

Paper D

Acoustic Comfort Investigation in Residential Timber Buildings in Sweden

Bard D., Vardaxis N.-G., Sondergaard E., Journal of Sustainable Architecture and Civil Engineering, 24(1), 2019, 78-89.

Paper E

Evaluation of noise annoyance in apartment buildings: associations of acoustic data to subjective responses., Vardaxis N.-G., Bard D.,

Submitted to Journal of Building and Environment in June 2019.

Paper F

Acoustic comfort assessment in heavyweight residential buildings: acoustic data associated to subjective responses.

Vardaxis N.-G., Bard D. ICA 2019, Aachen, Germany, September 9-13, 2019.

Appendix A

A.1 Questionnaire in English

A.2 Questionnaire in Swedish

Nomenclature

BBR	Boverket: Swedish national board of housing, building and planning.
CLT	Cross laminated timber
HW	Heavyweight
ISO	International Organization for Standardization
LW	Lightweight
PCA	Principal component analysis
SNQ	Single number quantity
WHO	World Health Organization

Part I

Introduction and study overview

1. Introduction

Hearing is the only sense that never stops being in function, not even when humans sleep. Sound is present everywhere. In the quietest place, one could still hear the background noise such as the wind or other natural sounds coming from the water or the birds. Sounds of human activity such as walking steps often disrupts quietness too. This changes only in laboratory conditions, for instance in anechoic rooms where sound absorption is immense and the situation inside approaches absolute silence [Kuttruff 2006].

Sound climate is a vital part of everyday life and specifically the living sound environment at home, where people find shelter, feel safe and spend a considerable amount of their lives [Kuttruff 2006]. Studies in the field of building acoustics relate to the sound environment at home but approach acoustic conditions in housing from a merely technical perspective. They deal with sound transmission in a building structure, acoustic performance of building elements and measurements of sound pressure levels indoors [Vigran 2008].

The human factor, and hence perception of sound environment, is an important aspect to investigate when evaluating sound environments. Human perception varies according to parameters such as personal traits, sound sensitivity, emotional state, prior experience and of course the physiology of the human listening mechanism, the ear [Kleiner 2008]. Thus subjective response to sound cannot be described completely by acoustic measurement data such as the acoustic descriptors for characterizing building components. Subjective response to living sound environment has been part of many studies, mostly in terms of self-reported noise annoyance.

By definition, noise refers to the kind of sound that is unwanted, depending on the occasion [Kutruff 2006]. Noise is a main concern in building acoustics, since it is known that sounds can propagate through the various components and openings in a building: walls, floors, junctions, openings (doors, windows) etc. [Kleiner 2008]. Consequently, noise annoyance is a common problem in dwellings, especially multistory family apartment buildings [Rasmussen & Rindel 2010].

Generally, the problem of noise can lead to serious disturbances or even health damage. For instance, a noisy neighborhood street in a city center or a busy motorway next to dwellings can cause serious nuisances. Environmental noise has been reported as an important risk for public health and global authorities have established certain directives [WHO 2018]. Conflicts can also arise between neighbors, when somebody creates sounds that disturb others, e.g. music or television sounds, loud talking or partying in a flat.

Noise from neighbors has been reported in previous studies as the biggest indoors annoyance, in particular impact noise types like footsteps with bare foot and heels or kids jumping on the floor [Rasmussen & Rindel 2010, Vardaxis et al. 2018]. For such reasons there are regulations of accepted sound levels for noise outside a building or around a flat. The Swedish National Board of Housing, Boverket, has established acoustic regulations for dwellings in Sweden. Specifically, Boverket sets a minimum weighted standardized level difference index of $D_{nT,w,50}$=52 dB and a maximum weighted standardized impact sound pressure level index of $L'_{nT,w,50}$=56 dB as acceptable [Boverket 2016].

This thesis deals with the concept of acoustic comfort in apartments. Despite of being an important concept in building acoustics and engineering, acoustic comfort is hardly defined or analyzed in the literature. The term has been used in a general sense by engineers and designers, usually to refer to conditions with little noise or sound disturbances in a certain space. Past studies dealing with noise annoyance use acoustic comfort as a term having the exact opposite meaning of noise annoyance, but they do not define anything further.

A definition for acoustic comfort has been firstly provided in [Rindel 2002] and then developed further in [Rasmussen & Rindel 2005, Rasmussen & Rindel 2010], finally expressed as:

"a concept that can be characterized by absence of unwanted sound,

desired sounds with the right level and quality and

opportunities for acoustic activities without annoying other people".

This definition offers a user's perspective rather than merely a relation to measurement data. Acoustic comfort for a certain person, is a combination of the person as a receiver of sound as well as a source. That means, a person can be disturbed by his or her own sounds because the sounds are truly disturbing or just because others might be disturbed, and dissatisfaction or conflicts might arise.

1.1 Background

A literature review of acoustic surveys for noise annoyance in dwellings was conducted as the initial step for this thesis to establish a background and collect previous research outcome [Papers A, B and C]. The scope of the review is to examine those studies which combine acoustic data and subjective responses in order to approach acoustic comfort. The reviewed material concerns both field surveys and laboratory tests.

Some studies have been performed regarding noise annoyance in dwellings, based on various noise sources, indoors or outdoors. They measured the subjective noise annoyance of residents using surveys and reported high correlations between the acoustic descriptors and the annoyance responses in most cases. However, other studies demonstrated that noise annoyance is not always well associated to acoustic descriptors. For instance, subjective annoyance due to speech or music was found to have different associations to various indicators [Park & Bradley 2009] and in many cases associations were unsatisfactory.

Seemingly, metrics and descriptors utilized in order to assess building acoustic conditions, may not be representative of how residents perceive acoustics in their living environment. For example, tenants might have problems with noise or vibration transmission from neighboring flats in the low frequency range that is partially omitted from measurement spectra, as supported in a set of previous studies in Sweden [Ljunggren et al. 2014, Ljunggren et al. 2017].

Hence, a key concern is how well the perception of residents corresponds to the results acquired by acoustic measurements and the descriptors of sound insulation in buildings. The latter are defined in a list of related standards, and variations of these are sometimes proposed in order to achieve better levels of agreement. Statistical methods have been used to examine how well building acoustic descriptors associate to the subjective ratings of tenants, in field or laboratory studies. If they do, it is possible to formulate models for prediction of annoyance, satisfaction and comfort for the building users.

1.2 Aims and objectives

For the investigation of acoustic comfort, a multi-parametric approach was attempted in this study, an approach that combines elements from the fields of construction engineering, building acoustics, psychoacoustics, soundscapes and statistics. The final target is to develop a simple tool for acoustic comfort evaluation which is easy to use for engineers, acousticians, designers, consultants and the end users of apartments, i.e. the residents whether being owners or renters. To reach this goal the main concerns are to measure and evaluate acoustic conditions in apartment buildings and to develop prediction tools for acoustic comfort in housing.

Thus the overall goal of this study can can be summarized as:

To define, investigate, measure and evaluate acoustic comfort in apartment buildings.

The individual objectives are expressed as:

i. **To set up a background for the concept of acoustic comfort.**
ii. **To describe how residents perceive noise, acoustic qualities and comfort at home.**
iii. **To investigate the association between acoustic data and self-reported responses.**
iv. **To formulate acoustic comfort models and a descriptor for comfort in apartments.**
v. **To establish a reliable procedure for engineers to predict acoustic comfort.**

Some initial research questions that were developed at the start of this project are the following: What could be a definition of acoustic comfort for the living environment and how do people perceive acoustic comfort? How do they relate to sound or react to noise (especially low frequency impact sound) in their apartments and how much annoyed do they feel? What other emotions might arise due to the acoustic conditions at home? How do various types of noise in the living environments affect the inhabitants in relation to the types of building structure? How well could acoustic comfort be expressed with a simple indicator (single value) based on the combination of technical and subjective results? What is the gap between the engineering acoustic data and human perception? What kinds of new indicators and prediction models could be created? Could we finally formulate a valuable methodology combining certain tools for engineers to apply and even develop further?

1.3 Outline

For the implementation of this study, a research plan which includes a wide data collection from Swedish multistory residential buildings was set up. Multivariate analysis is conducted for a set of variables relevant to acoustic and building data, as well as subjective response to the sound environment at home. The scope was to investigate the association of acoustic data, construction data and self-reported data.

The final aim is to create a model and a new indicator to represent acoustic comfort in apartments. A schematic research plan is illustrated in Figure 1.1.

This thesis consists of two parts. Part I deals with all issues of the study and provide a research overview:

- Chapter 1 offers an introduction, laying out the aims and objectives.
- Chapter 2 offers a background on theory and measurements in building acoustics.
- Chapter 3 elaborates the concept of acoustic comfort.
- Chapter 4 introduces a set of statistical methods that were used for data analysis.
- Chapter 5 provides all the details of the research design and implementation of the survey.
- Chapter 6 provides summaries of the publications presented in the thesis.
- Chapter 7 discusses the conclusions and the novelties of this thesis as well as future work suggestions.

Part II includes the publications composed during this PhD project. A schematic summary of the published papers related to the research topics and the methods used is presented in Figure 1.2.

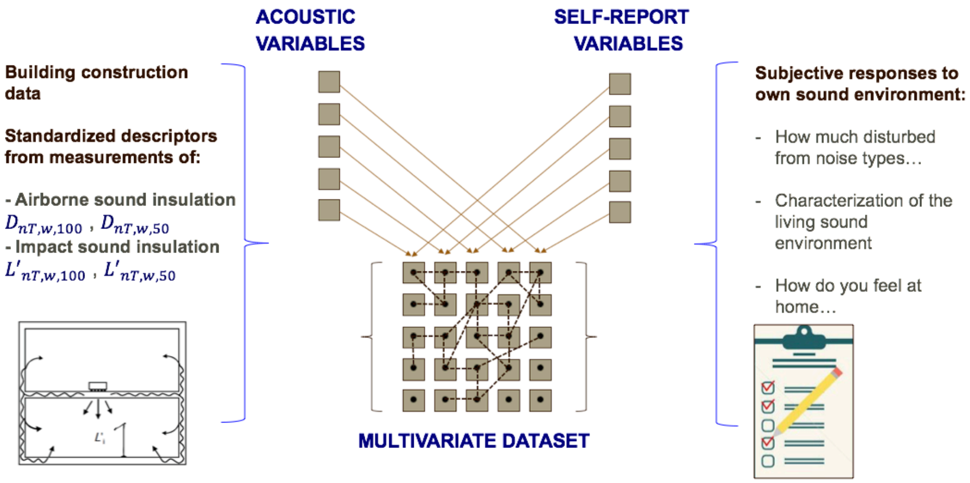


Figure 1.1 Outline of the research design and data analysis plan.

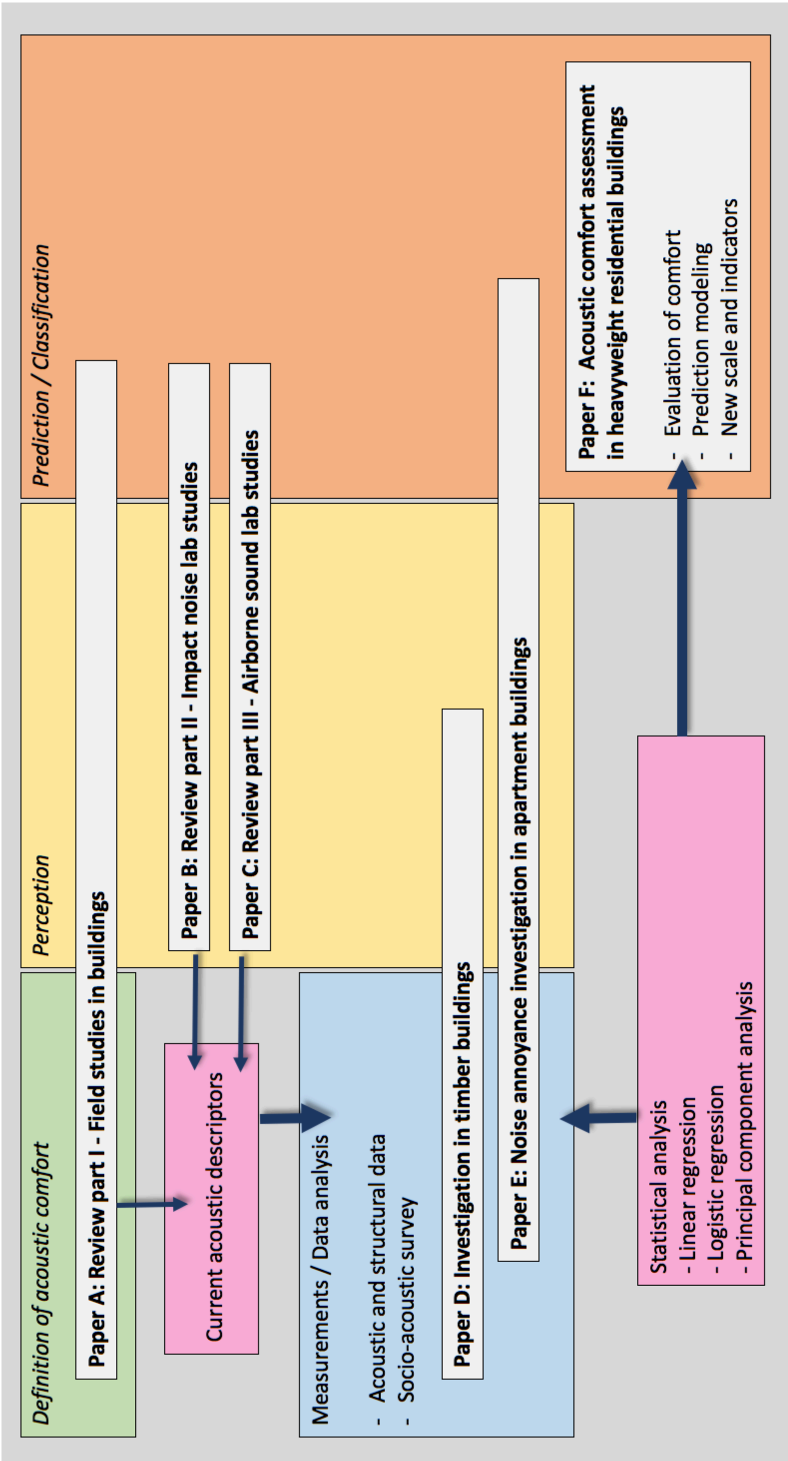


Figure 1.2 Flowchart showing the appended publications related to the research areas, the methods used and the connection among them.

1.4 Main contributions

This thesis sets a new fundament for acoustic comfort studies, providing contributions that previous research is lacking. The common way during similar past studies (analyzed in Paper A) was to investigate the association between subjective noise annoyance and acoustic descriptors as single number quantities (SNQ). That narrow approach is disrupted in this thesis, since more dimensions and parameters of interest are analyzed.

Firstly, variables concerning the structures and building information are integrated in the analysis to enrich the technical datasets. Then regarding the perception part, more self-reported variables are also included in the survey, such as emotional status, personal traits and subjective assessment of the sound environment. Demographic and other situational variables are also collected to a wider extent than in previous studies. Such parameters were utilized to develop a survey that ensures studying various parameters relevant to acoustic comfort, as well as other so called non-acoustic factors.

The research design of this study aimed at having a good variation of sample observations. Data from many buildings of various structure types were collected to ensure a good representation of Swedish buildings. Specifically, 101 building units of 34 different structure types were included in the total sample. This study is probably the biggest contemporary acoustic survey in terms of number of structures. Residents from almost 2000 flats were invited to participate in our survey, while in the end 537 responses were collected and 375 were used after filtering out data based on certain criteria. That sample size is fairly comparable to other studies, some of which gathered more observations: 800 replies in [Ljunggren et al. 2017], 702 in [Milford 2016] and 600 in [Bradley 2001]. The inclusion criteria of this study are stricter too, since the top floor residents were filtered out, due to dissimilar conditions to the rest of the occupants: top floor residents do not have neighbors and noise sources on the floor above. All the details for the survey design are described in Chapter 5.

Finally, novel contributions are provided regarding acoustic comfort evaluation in dwellings. Multivariate analysis was conducted and statistical models were developed for the prediction of subjective noise annoyance and emotional effects of a home's sound environment to the residents. Based on the latter, a new scale is constructed to assess acoustic comfort in the sample apartments. From that scale, a new indicator was evolved as a simple value, a SNQ that can be used for rating an apartment according to the acoustic comfort levels that it can provide to the occupants. In overall, a new set of tools is suggested in this thesis, that can be useful for acousticians, designers, engineers and residents.

1.5 Limitations

Every research study provides an outcome which is dependent on the research questions, the study design and the methods used. Consequently, there are limitations and shortcomings for this thesis and every study, due to the conditions and research planning, as well as additional factors. In particular:

1. The literature review provided in Paper A aimed at building a background of previous acoustic surveys related to acoustic comfort in apartments. However, there is a limited number of published papers about studies in the field, i.e. in real apartments and not laboratory setups. Because studies in real buildings are complicated, difficult in execution and costly in time and effort, many laboratory experiments have taken place to evaluate conditions relevant to noise annoyance at home. They are analyzed in the review parts for laboratory studies, in Papers B and C.
2. The sample size is a crucial parameter since it indicates how well statistical inference can be made, i.e. how robust conclusions can be made for a population based on the statistical result from the study sample. In the presented study the observations concern Swedish residents and the sample size is not sufficiently big to ensure statistical inference for the population. The same applies to the buildings of the sample, which come from the Green Building database, a Swedish archive from a national environmental research program. Most buildings are contemporary and fulfil minimum regulations similar to [Boverket 2016] which correspond to very good acoustic conditions. This means that the sample size cannot be considered representative of all Swedish dwellings. Thus generalizing the results of this thesis for every apartment in Sweden or another country is not suggested. Although 375 observations comprise a fairly good sample size, it is not possible to derive clear conclusions for some research questions.
3. Field studies in apartments can have multiple sources of error or bias. The collection of measurements can include deviations between sample apartments due to various reasons, mostly technical differences, external factors or random measurement errors. The same applies for the case of collected measurement data from other engineers: deviations might exist due to the human factor although they all follow the same standardized process. The situation in laboratory measurements might be controlled but

for field measurements, external factors (e.g. measurement noise) or random errors cannot be avoided with ease or certainty.

4. Questionnaire surveys might include various types of bias or random error too. Participants can misuse or misunderstand certain questions or information. Since every participant has a different personality, various bias can be introduced on the subjective responses. For instance, somebody might be strictly intolerant to any noise while another person might not pay attention at all. Such variability is observed in the collected results of this study. For instance, the self-reported responses of residents might be significantly different for groups of buildings of the same structure. That adds overall noise in the sample data and makes statistical modelling cumbersome.
5. Limitations exist for the statistical methods as well. The numerical models developed are based on the collected data which means they work for those datasets and then statistical inference is made about a population: Swedish apartment residents in this case. However, one should always consider that modeling imitates reality and cannot reproduce it completely. Hence there will always exist deviations from reality, which is the grand weakness of modeling.

2. Building Acoustics

There can be various sources of noise and vibration in a building, usually transmitted from one room to another through partitions and building components. The types of noise, the different sources, the building components, the ways of propagation and the measurement of components' sound insulation comprise the main topics of interest in building acoustics [Kleiner 2008]. An initial distinction is made according to the sound source between:

i. **Airborne sound transmission**, which refers to sound waves propagating through air. When those waves are incident on a partition they make it vibrate and then radiate sound to the other side of the partition. Typical cases of airborne sound in buildings are the human speech, sound systems (such as TV, HiFi or computer speakers) and appliances noise (e.g. ventilation system). Airborne sound may propagate through walls, doors, windows and sometimes floor or ceiling, as long as those components are excited by sound in the air. Most of the transmission also takes place in the air while a small amount of the initial energy is transformed in structure-borne waves, as illustrated in Figure 2.1 [Morfey 2001].

ii. **Impact sound or structure-borne sound transmission** which refers to sound and vibration created by a direct impact on a building component. This impact excites the partition and creates vibration and thus generates waves propagating trough other components and through the air. Walking on a floor (with heels or barefoot), kids jumping or dropping things on a floor are typical examples of structure-borne sound in apartment buildings (Fig. 2.2). Impact noise has been reported as the most disturbing sound source in previous acoustic surveys in apartments [Paper A, Milford 2016, Negreira 2016, Ljunggren 2017].

Both cases of airborne and impact sound can follow **direct and indirect transmission paths** between rooms and partitions. The indirect transmission path is called **flanking transmission** [Vigran 2008]. This happens for instance, when floor vibrations propagate through the connected load bearing walls and those walls radiate sound energy in the room below, which may also greater than the floor's radiation sometimes [Negreira 2016].

Flanking transmission is a very common problem in apartment buildings, especially for structure-borne sounds. Further, it can be a bigger problem in the case of lightweight (LW) wooden structures compared to typical heavyweight (HW) concrete structures [Negreira 2016, Hagberg 2018]. The acoustic behavior of wooden structures is usually worse than the heavy concrete ones in the low frequency range where most of the impact sound flanking transmission appears. The opposite can happen for airborne sound propagation, due to increased sound insulation in the contemporary lightweight building components [Ljunggren 2014, Forssén et al. 2008].

Sound insulation is a crucial topic in building acoustics. It refers to the noise reduction, for instance between two rooms when talking about apartments. The partition between the rooms, the floor or the wall, is characterized by its sound insulation properties derived by measurement data from standardized procedures, which are analyzed next. The airborne and impact sound measurements concern partitions between rooms (floors and walls) and ignore façade airborne sound insulation, which consist of different measurement steps.

2.1 Airborne sound measurements

Airborne sound insulation can be measured in a laboratory or in the field, i.e. on a real structure. In the first case, the lab consists of two adjacent rooms, completely isolated one from another but they are connected only with a common surface, which is the partition under measurement. This way it is possible to measure only the direct transmission path. For airborne sound insulation measurements, a sound source (a speaker) is used in the sending room to emit noise (white or pink steady noise). The sound pressure levels are measured in several microphone positions for at least 4 source positions, inside both test rooms, i.e. the sending and the receiving room [ISO16283 2014, ISO12354 2017]. An example of the such a setup is shown in Figure 2.1.

The test rooms are practically reverberation chambers, so they offer almost perfect diffuse field conditions, meaning equally probable distribution of the sound energy in all directions. This is a vital assumption during measurements because the recorded levels from several microphone positions in the test rooms are averaged. Thus the sound pressure levels are measured free of any inequalities from the sound field.

However, field measurements offer more realistic results about the general behavior of the test partition including any interactions from the structure, whether that is flanking transmission, resonances on certain frequency bands or other effects from the sound field. They take place in situ, i.e. having the source and receiver positions in the real rooms made from the building parts under investigation, as presented in Figure 2.1. So any influence from flanking transmission paths, through other building elements connected to the test sample (lateral walls, floor, ceiling) is included in the measurements [Vigran 2008].

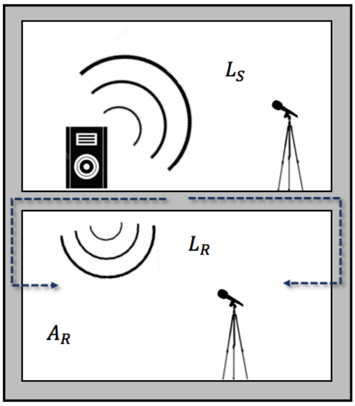


Figure 2.1 Measurement of airborne sound insulation in apartments.

Field measurements of airborne sound insulation rely on the definition of two standardized quantities: the apparent sound reduction index and the sound pressure level difference. They have been both described initially in ISO 140-4 (1998) and updated in the latest ISO 16283-1 (2014) and ISO 12354-1 (2017).

The **apparent sound reduction index**, denoted R' is defined as:

$$R' = L_s - L_R + 10 \, log \frac{S}{A_R},$$

where, L_s is the sound pressure level in the sending room in dB,

L_R is the sound pressure level in the receiving room in dB,

S is the area of the testing partition in m^2,

A_R is the absorption area of the receiving room in m^2 [Vigran 2008].

The absorption area, A_R, as mentioned before, is derived from Sabine's fundamental equation:

$$A_R = \frac{0.161 \, V_R}{T_{60}},$$

where V_R and T_{60} denote the volume (m3) and reverberation time (s) in the receiving room respectively. Reverberation time (RT or T_{60}) is the time in seconds for a recorded signal to decay 60 dB. In room acoustics terms, T_{60} is the time for the reverb, i.e. the contribution of a certain space to the direct signal (reflections, diffusion, absorption), to decrease by 60 dB from the first maximum level. The value of 0.5s is used for receiving rooms in dwellings for normalization. During field measurements, T_{30} or T_{20} (decay time for 30 or 20 dB) is often used instead due to higher background noise levels in the recorded signals [Kuttruff 2006, Vigran 2008].

The absorption area A (or effective surface) is the sum of every individual surface in the room multiplied by the corresponding absorption factor, a, in theory defined as:

$$A = \sum_{i=1}^{n} a_i S_i = a_1 S_1 + a_2 S_2 + \cdots + a_n S_n ,$$

The above mentioned absorption coefficient, a, is a value between 0 and 1, characterizing each material according to the percentage of sound energy absorbed by a certain surface (in a two dimensional setup). Consequently, reflective surfaces like concrete walls have absorption factors almost 0 while the a values of a thick mineral wool layer get closer to 1 [Vigran 2008].

The **standardized level difference**, denoted D_{nT} is defined as:

$$D_{nT} = L_s - L_R + 10 \, log \frac{T_{60}}{T_0}$$

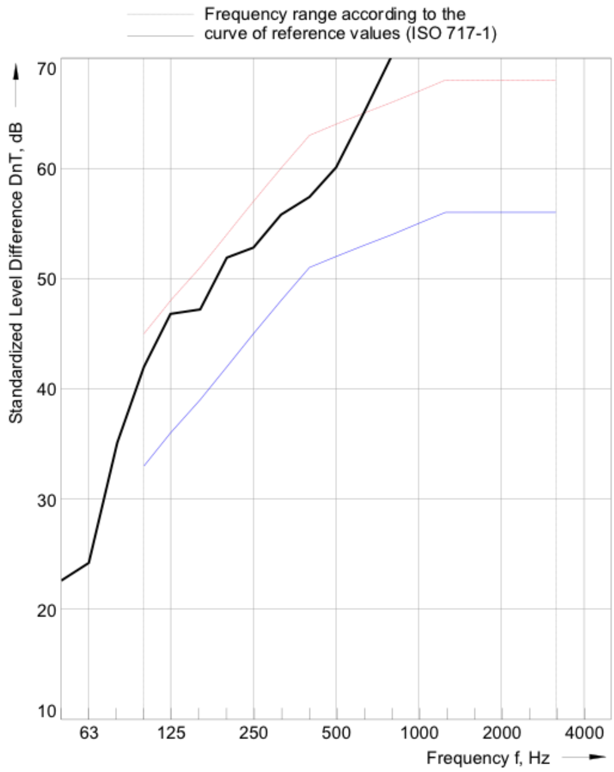
where T_0 is the standardization value for dwellings set to 0.5 seconds.

The quantities R' and D_{nT} are measured in 1/3 octave bands, as seen in Figure 2.2. However, it is preferable to have a single number value instead of a sound reduction curve for characterizing insulation of building components. Hence there is the weighted apparent sound reduction index, R'_w, or the weight standardized sound level difference $D_{nT,w}$.

The weighted indices are acquired by calculations using a predefined reference curve described in ISO 717-1 (1996), which a globally accepted reference curve. It has to be shifted in steps of 1 dB to the trend of the measured results, until the sum of the deviations between the two curves (the measured minus the reference) is not more than 32 dB, regarding all frequency bands available between 100 and 3150 Hz. Finally, the value of the shifted reference curve at 500 Hz is the one used as the weighted index R'_w or $D_{nT,w}$, according to the initially measured levels (see Figure 2.2).

Frequency f Hz	DnT 1/3 Octave dB
50	22,6
63	24,2
80	35,1
100	42,0
125	46,8
160	47,2
200	51,9
250	52,8
315	55,8
400	57,4
500	60,1
630	65,0
800	70,3
1000	73,5 B
1250	73,7
1600	74,8
2000	75,3 B
2500	76,1 B
3150	76,0 B
4000	76,9 B
5000	75,2 B

B: DnT >= value shown



Rating according to ISO 717-1
$D_{nT,w}(C;C_{tr})$ = 64 (-1; -7) dB

$C_{50\text{-}3150}$ = -7 dB; $C_{50\text{-}5000}$ = -6 dB; $C_{100\text{-}5000}$ = 0 dB;
$C_{tr,50\text{-}3150}$ = -20 dB; $C_{tr,50\text{-}5000}$ = -20 dB; $C_{tr,100\text{-}5000}$ = -7 dB;

Figure 2.2 Example of airborne standardized level difference measurement curve in black, reference curve in blue and shifted reference curve in red.

2.2 Impact sound measurements

Similar to airborne sound, there can be measurements in the exact same laboratory setup or in situ for impact sound. The impact sound pressure levels are measured then, to characterize the insulation properties of a component regarding impact sound, only this time the sound transmission is actually measured (not the reduction). The sound source utilized for impact sound measurements is also different, which is the standardized tapping machine specified in ISO 140-6 (1998). This is a standardized measurement device with 5 hammers weighting 0.5 kg each and they hit the floor in the sending room twice per second, with a frequency of 10 Hz [Vigran 2008]. The radiated sound power is measured only in the sending room in several microphone position for at least 4 source positions [ISO16283 2014, ISO12354 2017]. Figure 2.3 illustrates the setup for impact sound measurements.

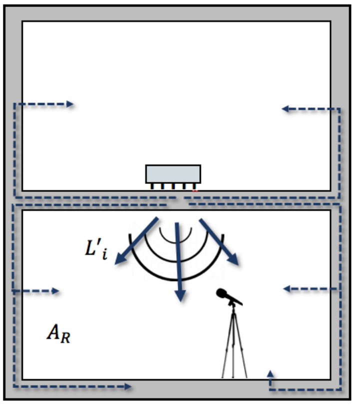


Figure 2.3 Measurement of impact sound pressure level in apartments using the standardized tapping machine. Flanking transmission paths indicated with dashed arrows.

The relevant quantity for impact sound measurements in the field is the apparent normalized impact sound pressure level, described initially in ISO 140-6 (1998) and updated in the latest ISO 16283-2 (2014) and ISO 12354-2 (2017). It is defined as:

$$L'_n = L'_i + 10 \, log \frac{A}{A_0},$$

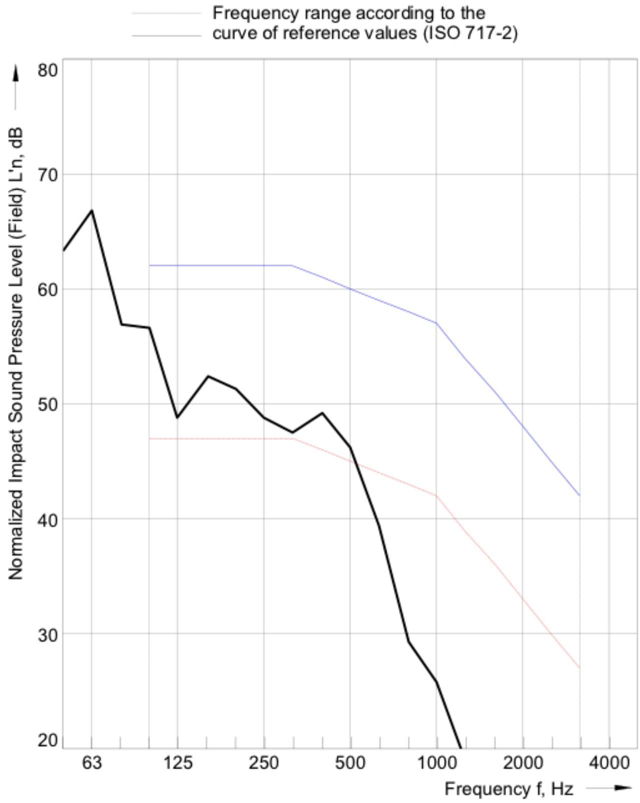
where A_0 is a reference value for normalization set at 10 m2. That quantity is usually expressed in field measurements relevant to the standardized reverberation time T_0=0.5 s. In this case it becomes the **standardized impact sound pressure level**, which is expressed as:

$$L'_{nT} = L'_i + 10 \log \frac{T}{T_0},$$

where L'_i is the in situ impact sound pressure level in the receiving room in dB.

Frequency f Hz	L'n 1/3 Octave dB
50	63,3
63	66,8
80	56,9
100	56,6
125	48,8
160	52,4
200	51,3
250	48,8
315	47,5
400	49,2
500	46,2
630	39,4
800	29,3
1000	25,8
1250	19,2
1600	17,2
2000	16,0
2500	11,3 B
3150	8,1 B
4000	8,6 B
5000	9,8 B

B: L'n =< value shown



Rating according to ISO 717-2
$L'_{n,w}$ (C_i) = 45 (0) dB $C_{i,50\text{-}2500}$ = 9 dB

Figure 2.4 Example of standardized impact sound pressure level measurement curve in black, reference curve in blue and shifted reference curve in red.

Then, for a single number quantity (SNQ) the weighted impact sound index can be acquired by calculations using the impact sound reference curve described in ISO 717-2 (1996). Again it is shifted by 1 dB steps until the sum of deviations (the measured minus the reference curve) is not more than 32 dB. The weighted index $L'_{nT,w}$ is then the value of the reference curve at 500 Hz (see Figure 2.4).

2.3 Acoustic descriptors

The weighted indices mentioned above for airborne sound insulation or impact sound levels are used to characterize the building components, e.g. a floor partition between two vertically connected rooms. They are also usually mentioned as acoustic descriptors, since they describe the acoustic properties of the structures under investigation.

There is also a variety of descriptors due to the addition of the spectrum adaptation terms C (or correction spectra) which are defined in ISO 717-1 and ISO 717-2 for the cases of airborne and impact sound descriptors respectively [ISO717 2013]. The C terms are SNQs calculated according to the frequency range so there is for instance $C_{I,100-3150}$. Then one can express $D_{nT,w,100}$=$D_{nT,w}$+$C_{100-3150}$ which is the weighted standardized sound level difference index with correction spectra in the official frequency range of 100-3150 Hz for airborne sound measurements according to the standards. Similarly there is $L'_{nT,w,100}$=$L'_{nT,w}$+$C_{I,100-2500}$ which is the weighted standardized impact sound pressure level index with spectrum adaptation terms in the official frequency range of 100-2500 Hz.

In this thesis work, the airborne sound descriptors $D_{nT,w,100}$ and $D_{nT,w,50}$ with C terms in the range of 100-3150 Hz and 50-3150 Hz respectively are used and analyzed. This is because the $D_{nT,w,100}$ values are the indicated acoustic descriptor from the standard. However, the Swedish regulation is stricter and imposes the use of $D_{nT,w,50}$ and $L'_{nT,w,50}$ with the narrow frequency range of measurements and relevant correction spectra [Boverket 2016]. Since most of the structures of this survey are Swedish, namely 32 out of 34, the imposed descriptors have to be studied alongside the ones suggested by the ISO standards. For the same reasons, for impact sound measurements we analyze $L'_{nT,w,100}$ and $L'_{nT,w,50}$ with C terms in the range of 100-2500 Hz and 50-2500 Hz respectively.

Additionally, the descriptors $D_{nT,w,50}$ and $L'_{nT,w,50}$ have been proposed to be used globally as harmonized SNQs since they correlate better with occupants' perception compared to other SNQs [Rasmussen 2010]. The overall results in the review of field acoustic surveys, presented in Paper A, indicate the same. Table 2.1 offers an overview of the existing descriptors according to ISO 717 (2013). However, more unofficial descriptors have been suggested in previous research derived from different proposed adaptation terms [Bodlund 1985, Ljunggren 2014, Virjonen et al. 2016, Ljunggren 2017].

Table 2.1 Overview of acoustic descriptors for field measurements according to [ISO 717 2013].

Acoustic descriptors for field sound insulation	Airborne sound insulation between rooms ISO 717-1	Impact sound insulation between rooms ISO 717-2
Basic descriptors	R'_w	$L'_{n,w}$
(weighted quantities)	$D_{n,w}$	$L'_{nT,w}$
	$D_{nT,w}$	
Spectrum adaptation terms	*None*	*None*
	C	C_I
	$C_{100-3150}$	$C_{I,100-2500}$
	$C_{50-3150}$	$C_{I,50-2500}$
	C_{50-500}	

2.4 Classification

The standardized measurement process and the aforementioned acoustic descriptors are used to characterize structural components but they do not represent exactly acoustic conditions in living environments or acoustic comfort in apartments, which is the topic of this study. For this reason, several countries have suggested classification schemes based on acoustic descriptor values in order to define the living acoustic conditions.

Boverket or BBR, which is the Swedish National Board of Housing, has established some threshold of minimum acoustic performance. Namely BBR states a minimum level of weighted standardized sound level difference index of $D_{nT,w,50}$= 52 dB from the space outside to inside a dwelling and a highest weighted standardized impact sound pressure level index of $L'_{nT,w,50}$= 56 dB [Boverket 2016].

Furthermore, a classification system has been established according to certain requirement on airborne and impact sound, which has been also developed from national Swedish standards [SIS 2015, Boverket 2016]. The classes are presented in Table 2.2.

Table 2.2 Current classification system in Sweden [SIS 2015, Boverket 2016].

Sound class	D [dB]	C* [dB]	B [dB]	A [dB]
$D_{nT,w,50}$	< 52 dB	52**-55 dB	56-59 dB	> 60 dB
$L'_{nT,w,50}$	> 56 dB	56**-53 dB	52-48 dB	< 48 dB

* *called **BBR** class*
** *BBR threshold values*

3. Acoustic comfort

3.1 Definition of the concept

In this section, a further elaboration is attempted for the concept of acoustic comfort, which is the core topic of this thesis. The Cambridge dictionary defines comfort as:

- "a pleasant and satisfying feeling of being physically or mentally free from pain and suffering",
- "something that provides that feeling" or in other simpler versions,
- "something that makes life easy and pleasant" or,
- "being relaxed and free from pain" [Cambridge 2019].

Seemingly, comfort is explained as a state of feelings towards a situation, specifically a state which lacks negative affects (such as pain) and is approximately a state of relaxation. The literal explanation of comfort is related to pleasantness and satisfaction, two features which alongside noise annoyance have been involved in acoustic surveys relevant to subjective noise evaluation. Consequently, acoustic comfort is the state of comfort which relates to the acoustic conditions in general, the sound environment and the sound stimuli around.

The only complete definition of acoustic comfort provided in the existing literature relevant to acoustics is the following: "a concept that can be characterized by absence of unwanted sound, desired sounds with the right level and quality, and opportunities for acoustic activities without annoying other people", which was firstly expressed by [Rindel 2002], then in [Rasmussen & Rindel 2005, Rasmussen & Rindel 2010]. Somebody can be the receiver of sound (or noise) but can also be the source. Also a person can be a source and receiver at the same time. The feeling of producing noise for others can be a negative factor for the state of somebody's comfort. For those reasons, we attempt in this study to approach acoustic comfort in a different manner, with a deeper focus on the human perception and emotions.

Another definition, coming from an acoustic study for office workspace [Chevret & Chatillon 2015], describes acoustic discomfort as "any intrusion of undesired sound interrupting a task, which demands attention and understanding." Consequently, acoustic comfort is also related to the activities of the people in a certain space and relevant to whether the proper acoustic conditions can be met, supporting the ongoing activities. Those conditions depend on the activity and the criteria set by people and the certain situation. Overall, acoustic comfort seems to rely on a balance between human demands, acoustic conditions and subjective perception.

A useful addition to the established definition is suggested in this thesis as:

"a concept with opportunities for supportive acoustic conditions according to the activities taking place".

This contribution aims to emphasize that the same person in the same space or the same set of acoustic conditions might be involved in various activities with different acoustic demands. For instance, one might need to talk loudly or discreetly to somebody, to read a book quietly, to sleep in silence, to listen to music or maybe play the piano and sing at home. Some of those activities have acoustic demands such as low sound levels (silence) or sufficient insulation and limited reverberation for music exercise.

Summing up, according to the established definitions given in [Rasmussen & Rindel 2010] and a small contribution given in this thesis, acoustic comfort is defined as a concept described by:

- Absence of unwanted sound (i.e. noise),
- Desired sounds with the right level and quality,
- Opportunities for acoustic activities without annoying others,
- Opportunities for supportive acoustic conditions according to the activities taking place.

3.2 Approaches for comfort in acoustics

It is important to note that so far acoustic comfort issues are treated entirely as noise annoyance problems, although the term acoustic comfort has been widely used in the branches of building and room acoustics. Researchers in previous studies collected acoustic data from sound insulation descriptors and associated that data to self-reported noise annoyance of the residents [Ljunggren et al. 2014, Hagberg and Bard 2014, Milford et al. 2016, Ljunggren et al. 2017, Hagberg 2018]. In some other cases, the acoustic descriptors were used as equivalent to an acoustic comfort index without considering any subjective response.

A detailed review of field studies relevant to acoustic comfort, studies that associate acoustic data to self-reported noise annoyance, can be found in Paper A. However, sound insulation performance of building elements and related sound pressure levels within a room cannot be considered the only contributors to the state of acoustic comfort. Because such indicators are designed to measure sound transmission properties. A subjective noise annoyance study, following this usual approach, is presented in this thesis in Papers D and E.

Another approach for the evaluation of environments has been followed in the research of soundscapes. A definition of the term soundscape has initially been given as "an environment of sound (or sonic environment) with emphasis on the way it is perceived and understood by the individual or by a society" [Truax 1978]. Recently, soundscape was defined in the ISO standards as being: "an acoustic environment as perceived or experienced and/or understood by a person or people, in context" [ISO12913 2014].

Soundscapes include many types of sound stimuli in an environment that can happen individually or in the same time. A background ambience and several random noise events or other sound stimuli (more than one) can comprise a soundscape [Truax 1978]. For example, that might be an outside public space: a street or a park. Apparently, such an approach can be applied for indoor climates as well, such as the living sound environment of an apartment. A soundscape approach is utilized for the evaluation of acoustic comfort in Paper F: this study is based on the emotional reactions of the residents towards their own sound environment at home.

4. Statistical methods

4.1 Basic sample statistics

This section provides a summary of fundamental statistical quantities that are involved in all the methods of this chapter [Rawlings et al. 1998, Johnson & Wichern 2013]. The mean is the average value of n observations and it is the most common statistic used as an estimator of the population mean. The sample mean for a variable k is defined as:

$$\bar{x}_k = \frac{1}{n}\sum_{i=1}^{n} x_{ik}$$

and it can be combined into the mean vector:

$$\bar{x} = \begin{pmatrix} \bar{x}_1 \\ \bar{x}_2 \\ \vdots \\ \bar{x}_p \end{pmatrix}$$

The variance is a measure of spread. The sample variance s_{ii} *or* s_i^2 is formulated as:

$$s_i^2 = \frac{1}{n-1}\sum_{i=1}^{n} (x_{ik} - \bar{x}_i)^2$$

The standard deviation is also widely used to indicate spread, which is defined as:

$$s_i = \sqrt{s_i^2}$$

The sample mean and variance together can be used to describe the distribution of a variable if that is a normal distribution. The latter is the most common distribution, denoted as $N(\mu, \sigma^2)$ for a population with mean and variance μ and σ^2 respectively. The sample mean and variance can be used instead for approximation from the data as $N(\bar{x}_i, s_i^2)$.

In many cases two different variables in a dataset are examined together. Then the joint variability of variables is of interest and there is measures for that such as the covariance and the correlation. The sample covariance between variables i and j is defined as:

$$s_{ij} = \frac{1}{n-1}\sum_{i=1}^{n}(x_{ik} - \bar{x}_i)(x_{jk} - \bar{x}_j),$$

and can be combined into the covariance matrix:

$$S = \begin{pmatrix} s_{11} & s_{12} & \cdots & s_{1p} \\ s_{21} & s_{22} & \cdots & s_{2p} \\ \vdots & \vdots & \ddots & \vdots \\ s_{p1} & s_{p2} & \cdots & s_{pp} \end{pmatrix}$$

Correlation is the most common measure of linear association between variables which varies between -1 and 1. A correlation close to 1 means that the two variables vary in the same direction while a value close to -1 means they vary to the opposite direction. Nothing changes if a constant is added or if a positive constant is multiplied to a variable. The sample correlations between variables i and j is:

$$r_{ij} = \frac{s_{ij}}{\sqrt{s_{ii}s_{jj}}},$$

while the values can be combined into the correlation matrix:

$$R = \begin{pmatrix} 1 & r_{12} & \cdots & r_{1p} \\ r_{21} & 1 & \cdots & r_{2p} \\ \vdots & \vdots & \ddots & \vdots \\ r_{p1} & r_{p2} & \cdots & 1 \end{pmatrix}$$

4.2 Reliability analysis

When using questionnaire items with scores on certain scales (e.g. Likert style scales) it is necessary to test the internal consistency. For this reliability analysis can be performed, a method relying on Cronbach's Alpha (α) value [Tavakol & Dennick 2011, Bland & Altman 1997]. The latter is a statistic which measures internal consistency between items on a scale, meaning consistency between different responses on a questionnaire scale in this study.

Alpha takes values between 0 and 1 to provide a measure for internal consistency for a scale. This means all the items of a questionnaire measure the same concept or comply with the scale construction, thus the items are inter-related. The formula of Cronbach's Alpha is:

$$\alpha = \frac{k}{k-1}\left(1 - \frac{\sum s_i^2}{s_T^2}\right)$$

where k is the number of items in the reliability analysis (i.e. variables, questions on the same scale). Then s_i^2 denotes the variance of the i-th item and s_T^2 is the total variance, as found after summation of all items [Bland & Altman 1997]. Noticeably, the scale items should be enough (more than two responses in comparison).

Additionally, the direction of the scale, e.g. positive-negative, should be the same for all items (variables) in a reliability test. Otherwise some scales in the dataset should be recoded/reversed in order to have the same direction.

The acceptable values of Cronbach's Alpha (a) are not strictly defined and thus researchers have to determine some thresholds depending on every occasion. However, there is a rule of thumb classifying alpha values as:

- (a < 0.5): Problematic
- (a < 0.7): Low
- ($\boldsymbol{a}$ > 0.7): Adequate
- ($\boldsymbol{a}$ > 0.8): Excellent
- (a > 0.95): Too much (redundant)

The number of observations, the length of a test or set of items which is tested affects the result of alpha as well. A very small sample size (e.g. n<15) or very few items can result to acquire a small alpha. To increase the alpha values, more items should be added. However, if there is too many items in the test, extremely big values might me acquired, e.g. higher than 0.95. This would indicate that too many items correspond to the same scale and dimension and they might be redundant.

The concept of reliability follows the assumption of unidimentionality for a sample of test items [Tavakol & Dennick 2011]. If the latter is violated, the results might be wrong. The reliability test is supposed to be used for items with the same scale. Thus if different scales are used within the same survey (or questionnaire) the tested items should be grouped according to the scale type and they would correspond to different dimensions. Factor analysis could be additionally performed to identify underlying dimensions if needed. Reliability analysis was performed using IBM SPSS Statistics 24 to test the consistency of questionnaire items in Paper E and F.

4.3 Mann-Whitney U test

A non-parametric test was employed to test the effect of variables on the annoyance responses, namely the Mann-Whitney U test. This operates under the assumption of similar distributions (not normal) for ordinal independent observations [Sheskin 2000]. The scales used for the responses in this survey are 5-point Likert type scales [Jamieson 2004], namely ordinal scales ranging from 1 to 5. The *U* value determines the significance of differences between two sample medians and it is defined as:

$$U_i = n_1 n_2 + \frac{n_i(n_1+1)}{2} - \sum R_i$$

where n_i is the sample size for different groups indexed *i*=1 or 2. $\sum R_i$ denotes the sum of ranks of each test group. The smaller of the two values U_1 and U_2 is the final *U* statistic and is compared to the relevant table of predetermined critical values like other similar tests [Sheskin 2000]. *U* tests were employed to test the differences between groups on the annoyance responses (Paper E) and the emotional reactions to home sound environment (Paper F). The analysis was performed using IBM SPSS Statistics 24.

4.4 Linear Regression

This is a simple method to establish a linear relation between a response (dependent variable) and one or more explanatory (independent) variables. It can take the form of:

$$Y_i = b_0 + b_1 X_{1i} + b_2 X_{2i} + \cdots . + b_p X_{pi} + e_i,$$

where Y is the modeled response, X_{pi} denotes the predictor (explanatory) variables and $b_0, b_1, \ldots$ are the model coefficients and e is the model error [Rawlings et al. 1998]. Linear regression models can take the matrix form of:

$$y = X\hat{\beta} + e$$

Application of linear regressions depends on the following assumptions:

- Y_i is a continuous variable and follows a random distribution,
- X_i is a non-random independent variable,
- there is a linear relationship between *X* and *Y*,
- the residuals of the regression model are randomly distributed with $N(0, \sigma^2)$.

In linear regression the least squares approximation is followed for the estimation of the coefficients $\hat{\beta}$. The ordinary least squares algorithm calculates the coefficients as [Rawlings et al. 1998]:

$$\hat{\beta} = (X^T X)^{-1} X^T y$$

A crucial quantity in linear regression is the determination coefficient R^2 which is a measure of how much the independent variable contribute to the model. It represents the total variance explained by the model and it is defined as:

$$R^2 = \frac{SS(Regr)}{\sum y_i^2},$$

where $SS(Regr)$ denotes the sum of squares due to regression model. In the simple linear regression, with a single predictor, this is equal to ${b_1}^2 \sum(x_i - \bar{x})^2$ or better it is the correlation coefficient squared. In the multiple regression case $SS(Regr)$ is more complicated and explained with matrix notation in [Rawlings et al. 1998]. Linear models were developed using IBM SPSS Statistics 24 and they are presented in Paper F.

4.5 Rescaling

To model the responses of the residents, the acoustic descriptors and other variables are used as explanatory variables. For the annoyance responses of our questionnaire there is an ordinal categorical scale of 1-5: that is not a linear scale thus the application of linear regression in such a case is improper. Even for the case of 11-point scales used in previous acoustic surveys, the use of linear regression is based on the assumption that a questionnaire scale 0-10 is linear, which is questionable. There have been debates about the character of Likert-type scales which suggest that those scales should not be treated as linear in analyses [Jamieson 2004, Carifio & Perla 2017, Agresti 2007].

Further, the observations grouped by test structure blocks an uneven distribution: some blocks have less than 10 observations while few others have up to 20 or even 50 (see Figure 5.3). The histograms of subjective responses indicate also skewed distributions (see Paper E). Hence, no assumption of normal distributions can be made.

The appropriate statistical method to analyze such categorical responses is logistic regression. But for the 5 categories (Not at all, Slightly, Moderately, Very, Extremely) to be analyzed appropriately in a multinomial logistic regression model a sufficient sample size in each category would be necessary. While most of the subjects' replies are located in (1-Not at all and 2-Slightly) there is not a big sample size for each three other categories of higher disturbance options 3-5.

Therefore, the 5-point responses were rescaled in binary ones, which are not linear but appropriate for binary logistic regression. There is a certain methodology applied in noise annoyance surveys to establish dose-response models which predict the percentage of annoyed or highly annoyed subjects (indicated as %A, %HA). It is a convention in the field of annoyance investigation where the scores of 1-5 were translated in values 0-100 following the same rule as in [Miedema & Vos 1999]. The provided formula is:

$$score_{(0-100)} = 100(i - \tfrac{1}{2})/m,$$

where m denotes the number of existing categories (5 in this case) and i denotes the rank of a category. That leads to the following midpoints: 10, 30, 50, 70, 90 for m=5. Scores from other common Likert-type scales, e.g. 1-7 or 0-10 can be rescaled following the same rule with the relevant m ordinal categories.

Then a cutoff value of 50 was used in order to define the %A which refers to the percentage of annoyed subjects: replies of 50 and higher are classified as annoyed for the binary responses. The same could be applied for highly annoyed subjects (%HA, cutoff value at 72). It was neglected in this study though due to few only observations in that range and lack of interesting results. Hence, replies 3-5 in this study's scales were simply classified as annoyed, while replies 1-2 were classified as not annoyed.

4.6 Logistic regression

After rescaling, binary logistic regression is applied treating category 1 as success (the event of achieving no annoyance) and category 0 as failure. This is a non-linear method which uses odds to construct a linear relation and has the form of:

$$log\left(\frac{P_i}{1-P_i}\right) = b_0 + b_1X_{1i} + b_2X_{2i} + \cdots . + b_pX_{pi} \, ,$$

where P_i is the probability of success estimated by the model, in this case the probability of no annoyance. Then b_0, b_1,..., b_p are the estimated coefficients (b_0 being the intercept) and X_{1i} - X_{pi} are the independent variables used in the model [Agresti 2007].

To test if an independent variable X_{1i} has a significant effect on predicting the probability of the outcome, Wald's test and the Z value is used. Statistical significance can be proven when testing the null hypothesis H_0*:* $b_j=0$ against H_1*:* $b_j \neq 0$. When H_0 is true then:

$$Z = \frac{b_j - 0}{SE(b_j)} \approx N(0,1)$$

and if Z is large enough the H_0 is rejected at s significance level *α (=0.05)*. For $|Z| > |\lambda_{\alpha/2}|$ the corresponding probability is derived indicating statistical significance for $p<0.05$ [Agresti 2007].

For nested models (i.e. models with at least one common independent variable) we can use the Deviance D for comparison, defined as:

$$D = -2lnL(b) \sim \chi^2(n-(p+1)),$$

where $L(b)$ denotes the likelihood function evaluated for the coefficients matrix, n is the number of observations and p+1 the total parameters of the model (+1 accounts for the intercept). Thus, smaller deviance accounts for better models [Agresti 2007].

The model information criteria that we use for comparing non-nested models are the Akaike's information criteria (AIC) and the Bayesian information criteria (BIC), calculated as:

$$AIC(p+1) = 2(p+1) - 2lnL(b) = 2(p+1) + D \text{ and}$$

$$BIC(p+1) = (p+1)lnn - 2lnL(b) = (p+1)lnn + D.$$

Similarly to the deviance, the AIC and BIC values are based on $L(b)$ and the number of model parameters; thus the smaller the criteria values the better. AIC usually underestimates the final values compared to BIC. For statistic entities similar to the coefficients usually reported in linear regression, the pseudo-R^2 values according to Cox-Snell and Nagelkerke are presented and defined as [Agresti 2007, Nagelkerke 1991]:

$$R^2_{Cox-Snell} = 1 - \left(\frac{L(b_0)}{L(b)}\right)^{2/n} \; with \; 0 \leq R^2_{Cox-Snell} \leq 1 - \left(L(b_0)\right)^{\frac{2}{n}} \text{ and}$$

$$R^2_{Nagelkerke} = \frac{R^2_{Cox-Snell}}{1-(L(b_0))^{2/n}} \; with \; 0 \leq R^2_{Nagelkerke} \leq 1,$$

which is more convenient to use as it can vary between 0 and 1, in the same manner as linear regression coefficients. But those pseudo coefficients do not really represent the variance explained by a model; such interpretation is valid only in linear regression. The pseudo-R^2 values serve as means of comparison between logistic regression models, in combination with the AIC/BIC values in order to compare two different models. Thus a model with high R^2 and low AIC/BIC is clearly better. Priority is put on the AIC/BIC values for model evaluation [Agresti 2007]. In this study we specifically use $R^2_{Nagelkerke}$ and BIC, which are easier to understand and convenient for clearer comparisons in our case. However, we present all the above model information for transparency because there is no standardized criterion [Agresti 2007, Nagelkerke 1991].

However, all the above criteria work for models with various predictors on the same response. To compare models concerning different responses (and predictors) one needs a different measure, which is the ROC (Receiver Operating Characteristic) curves and the corresponding AUC or AUROC (area under the ROC curve). ROC and AUC comprise a goodness-of-fit test for binary regression and represent the percentage of correctly classified observations from a model. Specifically, ROC curves illustrate the sensitivity on y-axis and (1-specificity) on x-axis. Sensitivity is the proportion of true success (i.e. response of 1) classified correctly. Specificity is the proportion of true failures (i.e. 0) classified correctly as failures [Agresti 2007, Huber-Carol et al. 2002].

Higher AUC values correspond to a high prediction efficiency of the tested model. The probability of 0.5 corresponds to an AUC of 50%, which means correct classification of outcome due to chance. A model has to predict better than that to be successful. Hence, AUC values above 50% are considered acceptable, above 70 % satisfactory and above 90% very good.

Finally, logistic regression was performed using the programming language R (version 3.3.3) in Paper E. The logistic regression models were developed with the glm() function and the pseudo-R^2 and BIC values were acquired by the “pscl” package functions [Jackman 2017]. The ROC curves and AUC values were acquired using the “pROC” package [Robin 2011].

4.7 Principal components analysis

There is often the need during statistical analyses to find an underlying structure of dataset, usually because there are many variables to be tested and that has certain difficulties. It might be very complex to treat a big dataset or there might be a demand to give priority on some variables without knowing which ones should those be. There exist acknowledged dimension reduction techniques for such cases and principal components analysis (PCA) is one of the most common. Analyzing the variance-covariance structure of a dataset exploring linear combinations of the variables is the key idea of PCA. The total variability of the dataset is explained by the principal components which all of them can reproduce the original information of the explored variables. Hence, those variables can be replaced for further analysis by some principal components, represented by linear relations of the variables on the components [Johnson & Wichern 2013, Vidal et.al. 2003].

In overall, PCA is a dimension reduction technique which finds linear covariations in multidimensional data and constructs some dimensions, the components, based on the strength of that covariations. To explain that operation, assume $\boldsymbol{X}$, a random vector and another matrix a (both of dimension p). Then, the observations matrix $\boldsymbol{Y}$, can be formulated as

$$\boldsymbol{Y} = \boldsymbol{a}^{\boldsymbol{T}}\boldsymbol{X}$$

and thus $\boldsymbol{Y}$ will have a variance of

$$Var(Y) = \boldsymbol{a}^{\boldsymbol{T}}\boldsymbol{\Sigma}\boldsymbol{\alpha}$$

where $\boldsymbol{\Sigma}$ is the covariance matrix of $\boldsymbol{X}$.

The biggest variation of the data should be represented by some linear combination, and that is a main question in PCA: which direction, as represented by a, can show the maximum variability of the observations. Notably, a is normalized in order to be of unity length [Johnson & Wichern 2013].

The linear combination $a^T X$ will have the largest variance under the restriction that

$$\boldsymbol{a}^{\boldsymbol{T}}\boldsymbol{a}=1.$$

The Cauchy-Schwarz inequality suggests that for a $\neq 0$,

$$max\frac{\boldsymbol{a}^{\boldsymbol{T}}\boldsymbol{\Sigma}\boldsymbol{\alpha}}{\boldsymbol{a}^{\boldsymbol{T}}\boldsymbol{a}}$$

is equal to the biggest eigenvalue of the covariance matrix $\boldsymbol{\Sigma}$**.** Then that is acquired for $a_1 = e_1$, the eigenvector corresponding to the biggest eigenvalue and standardized to $e_1^T e_1$=1. That eigenvalue is considered to be the first principal component.

Accordingly in PCA one should find the $e_1, \dots, e_p$ which are orthogonal eigenvectors of of $\boldsymbol{\Sigma}$. The corresponding eigenvalues are denoted λ_i, $i = 1, \dots, p$. The principal components of $\boldsymbol{X}$ are $e_1^T\boldsymbol{X}$, ..., $e_p^T\boldsymbol{X}$. If a matrix $\boldsymbol{P}$ has columns e_i then

$\boldsymbol{P^T}(\boldsymbol{X}-\boldsymbol{m})$ has a normal distribution of $\boldsymbol{N_p}(0,\boldsymbol{\Lambda})$ where Λ is the diagonal matrix of the eigenvalues.

The columns of $\boldsymbol{P^T X}$ are the principal components and the original observations X can be reconstructed from the relations $e_1^T X$, ..., $e_p^T X$ because $\boldsymbol{X}=\boldsymbol{P}\boldsymbol{P^T}\boldsymbol{X}$ or $\boldsymbol{X}=\sum_i (e_1^T \boldsymbol{X})\, e_i$.

An important concept in this method is the variance explained by the identified components. The total variance is:

$$\sum_{j=1}^{p} Var(Y_j) = \sum_{j=1}^{p} \lambda_j = tr(\Sigma) = \sum_{j=1}^{p} Var(X_j).$$

Thus the j-th principal component explains a proportion of the total variance equal to

$$\frac{\lambda_j}{\lambda_1+\lambda_2+\cdots\lambda_p} = \frac{\lambda_j}{\sum_1^p \lambda_j}\,.$$

Then the i-th largest principal components explain together the proportion

$$\frac{\sum_{k=1}^{i} \lambda_k}{\sum_{j=1}^{p} \lambda_j}.$$

The covariance between Y_i and X_j is $Cov(Y_{i,}X_j) = \lambda_i e_{ik}$ and it holds that $\rho_{Y_{i,}X_j} = \sqrt{\lambda_i} e_{ik}/\sigma_j$ where e_{ik} is element k in the eigenvector i to $\boldsymbol{\Sigma}$. Then the covariance between the i-th principal component and variable k is equal to $e_{ik}\sqrt{\lambda_i}$.

Another fundamental consideration in PCA is the scale of the variables included in a dataset. Some statistical procedures are scale invariant and the units of a variable do not affect the conclusions of the process, but not in PCA. If the multivariate variables are in the same numerical scale, then PCA can be performed in the original scale. Otherwise, the data should be standardized if initially measured on different scales [Johnson & Wichern 2013]. For the implementation of PCA in Paper F, the software IBM SPSS Statistics 24 was employed.

5. Survey implementation

5.1 Research sample of buildings

The total sample of buildings contains 101 different units of 34 various structure types: 25 heavyweight concrete structures, 7 lightweight timber structures and 2 mixed ones. The term heavyweight (HW) structures refer to typical concrete buildings with concrete frame and floors. They might have walls made of bricks, heavier components such as concrete wall panels or light wall panels of any type. The term lightweight (LW) concerns wooden structures in this study, all 7 of which have frames and floors made of cross laminated timber (CLT). Their walls are usually CLT components or light wooden wall panels with insulation. Mixed structures can vary a lot, while in this study there are only two specific cases: (i) a modern structure consisting of a steel frame with light concrete floors and brick walls and (ii) an old-type structure of masonry walls with wooden frame and floors.

Each structure corresponds to an urban block of identical buildings. Some structure blocks have more than one building unit repeated in many cases, which is typical of housing in Scandinavia. For instance, there is a case of a sample structure with 10 buildings units with different addresses in the same land plot. Hence, every structure block mentioned in this thesis contains between 1-10 building units of the same structure type in the same urban block on the map. The same applies to the observations, which refer to the replies of residents in test apartments. The observations are grouped in 34 structure blocks based on the structure details of each block.

Most structures are located in Sweden, namely 32 another 2 are Danish structures. A complete list of the study's structures is tabulated in Table 5.1. Acoustic measurements data was collected for the test structures. The data comes from the "Green Buildings" database, which is an archive from a national Swedish research program about sustainable housing in Sweden, including acoustic conditions research and development. All those measurements are standardized and performed by professional acousticians. For the first 3 structures of Table 5.1, in situ acoustic measurements were performed by the author, according to the same standardized procedure of [ISO16283 2014, ISO12354 2017].

Following the template of previous field studies (as reviewed in Paper A) standardized measurements of airborne and impact sound were utilized between two adjacent rooms of the same size and position, one above another. The measured test rooms are bedrooms or living rooms, typical of the building's floor plan in all cases, as suggested in [Ljunggren et al. 2014, Hagberg 2018].

In the end, a single measurement between typical rooms from a sample building unit was used for each structure block. Since only a floor between two flats was measured in most cases, no more data was available in the "Green Buildings" database. In few cases more measurements existed, then the floor in the middle of the building's levels was chosen. Thus, if a building had 6 levels, the floor measurement between the 3rd and 4th level was selected to represent that structure type. Furthermore, only structures in the database that provided full measurement curves, besides the estimated descriptors, were included in the study.

Noticeably, the measurements in this study have a frequency range between 50-5000 Hz and the single number indices are calculated from 50 Hz, which is the standard in Scandinavia. The Swedish building regulations require a minimum weighted sound level difference of $D_{nT,w,50}$ = 52 dB from the space outside to inside a dwelling and highest weighted impact sound pressure level of $L'_{nT,w,50}$ = 56 dB [Boverket 2016]. However, other European countries have not so strict limits as they follow the official requirement of the ISO standards: 100-3150 Hz for airborne sound, 100-2500 Hz for impact sound measurements and descriptors with correction spectra C from 100Hz [ISO717 1996, ISO140 1998, ISO16283 2014, ISOEN12354 2017].

Thus in this study we use both descriptor types for analysis, the ISO suggested $D_{nT,w,100}$ $(= D_{nT,w} + C_{I,100-3150})$, $L'_{nT,w,100}$ $(= L'_{nT,w} + C_{I,100-2500})$ and the indices with extended frequency spectra and correction from 50 Hz, $D_{nT,w,50}$ and $L'_{nT,w,50}$. Table 5.2 presents some statistics for the single number quantities (SNQ) of the measurements, the acoustic descriptors calculated according to the relevant ISO standards. The original measured spectra (in 1/3 octave bands) for the airborne sound level difference D_{nT} and the impact sound pressure levels L'_{nT} and can be seen later in Figures 5.1 and 5.2.

Table 5.1 List of test structures in the survey

Structure number	Units	Building address	Post replies	Online replies	# Replies	# Flats	Response rate
1	2	Åsbovägen 12, 14, Fristad	8	2	10	44	22.7%
2	10	Vinkelvej 2, 4, 6, 8, 10, Kalkvarksvej 9B, 9C, 9D, 9E, Emilievej 1B, Fredrikshavn	15	2	17	60	28.3%
3	3	Thomas Laubs Gade 5, 7, 9, Copenhagen	0	6	6	23	26.1%
4	3	Solbergsvägen 38, 42,43, Upplands Väsby	5	2	7	71	9.9%
5	2	Torngatan 2A, 2B, Östervåla	3	0	3	27	11.1%
6	2	Sandåkersgatan 2, 4, Umeå	3	0	3	25	12.0%
7	2	Koggens gränd 1, 3, Malmö	9	3	12	24	50.0%
8	1	Åsbogatan 40 , Ängelholm	8	0	8	30	26.7%
9	1	Norra Trängallen 8, Skvöde	8	4	12	24	50.0%
10	4	Yxhammargatan 6A, 6B, 6C, 6D Falun	8	3	11	45	24.4%
11	2	Emil Lindells väg 28, 352 57 Växjö	11	8	19	57	33.3%
12	8	Sjöbågen 2A, 2B, 4A, 4B, 6A, 6B, 8A, 8B, Växjö	41	32	73	126	57.9%
13	4	Larssons berg 1, 3, 5, 7, Mölndal	8	4	12	30	40.0%
14	2	Centralvägen 4A, 4C, Upplands Väsby	0	2	2	18	11.0%
15	1	Mejerivägen 7, 117 43 Stockholm	5	9	14	55	25.4%
16	2	Stenunge allé 13, 15, Stenungsund	5	1	6	10	60.0%
17	9	Småbrukets Backe 30, 31, 32, 33, 35, 37, 39, 50, 60, Huddinge	43	31	73	420	17.4%
18	2	Sibeliusgången 2, 4, Kista	31	4	35	158	22.1%
19	3	Villatomtsvägen 6, 8, 10, Helsingborg	22	7	29	71	40.8%

20	2	Vallhamra torg 1A, 3A, Sävedalen	4	2	6	19	31.6%
21	8	Barbro Alvings gata 44, 48, 50, Emilia Fogelklous gata 8, Vantörsvägen 291, 295, 299, 301, Hägersten	10	11	21	86	24.4%
22	3	Linbastagatan 1, 3, 5, Helsingborg	6	3	9	61	14.8%
23	1	Topeliusgatan 8, Uppsala	2	0	2	8	25.0%
24	3	Duvbovägen 96A, 96B, Spånga	10	3	13	36	36.1%
25	1	Bergsslingan 109, Lerum	1	1	2	24	8.3%
26	3	Brandholmsvägen 46, 48, 50 Nyköping	4	5	9	20	45.0%
27	1	Svenljungagatan 1, Borås	11	5	16	44	36.4%
28	2	Fagningsgatan 6, 8, Stockholm	4	3	7	22	31.8%
29	2	Humblegatan 20A, 20B, Sundbyberg	3	8	11	60	18.3%
30	7	Årjängsgatan 1, 3, 5, Forshagagatan 76, 78, Karlskogagatan 6, 8, Farsta	18	10	28	84	33.3%
31	6	Barnängsgatan 5, 11, 24, 26, 28, 30, Stockholm	25	8	33	103	32.0%
32	6	Gärdebyplan 8, 10,14,18, 20,24, Spånga	5	4	9	40	22.5%
33	1	Färgfabriksgatan 18, Göteborg	7	3	10	16	62.5%
34	1	Barnhemsvägen 11, Nacka	3	4	7	23	30.4%
Structures	**Units**	**Total numbers**	**Post replies**	**Online replies**	**All #Replies**	**Apartments**	**Mean response rate**
34	101		347	190	537	1941	27.7%

Table 5.2 Acoustic data summary for the sample structures.

		Impact sound index in dB		Airborne sound level difference in dB	
		$L'_{nT,w,50}$	$L'_{nT,w,100}$	$D_{nT,w,50}$	$D_{nT,w,100}$
Type:	N*	Mean (Range)		Mean (Range)	
Heavyweight (HW)	25	50.2 (40-65)	49.7 (39-64)	57.7 (44-64)	58.1 (44-65)
Lightweight (LW)	7	52.4 (49-59)	49.6 (47-54)	55.5 (48-63)	56.4 (48-65)
Mixed	2	52.1 (47-61)	51.2 (47-59)	56.9 (48-62)	56.9 (48-62)
All structures	34	50.8 (40-65)	49.7 (39-64)	57.2 (44-64)	57.7 (44-65)

*N denotes sample size

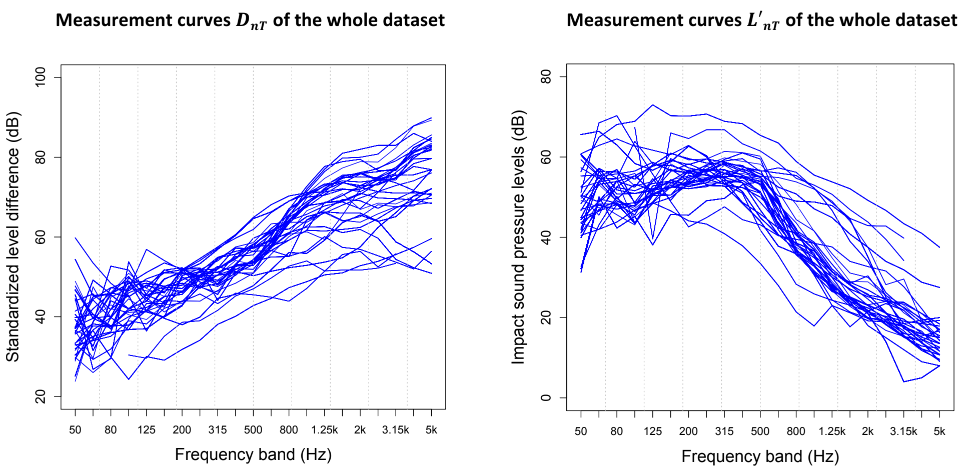


Figure 5.1 One third octave band curves of airborne and impact sound measurements of the dataset.

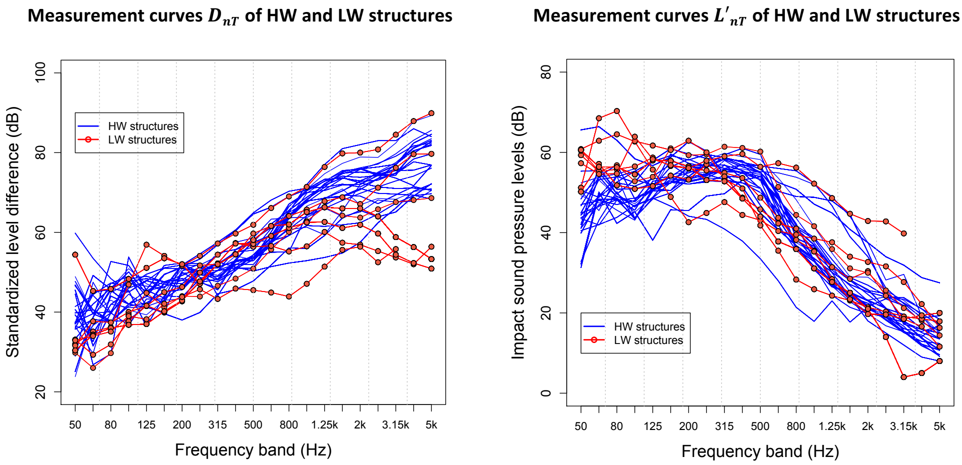


Figure 5.2 One third octave band curves of airborne and impact sound measurements of the 31 Swedish heavyweight (HW) and lightweight (LW) structures, as presented for comparison in Paper F (Danish and mixed structures filtered out).

5.2 Self-reported data collection

Besides the technical data (acoustic descriptors, building parameters) there is also the subjective data, which measures the perception of the participants in the survey (also referred to as subjects). This self-reported data was collected with a socio-acoustic survey, using a questionnaire for the residents developed according to [ISO 15666 2003] and previous acoustic surveys regarding field studies in dwellings [Ljunggren et al. 2014, Hongisto et al. 2015, Ljunggren et al. 2017]. A permission was requested and granted from the Research Ethics Board in Lund, Sweden, for conducting this survey., which took place between September 2016 and February 2018.

The questionnaire aimed to capture several aspects that are considered part of the overall acoustic comfort concept, such as noise annoyance, emotional reactions and characterization of the sound environment, as well as demographic information of the participants. The distribution was initiated with post mail to every flat of the test buildings. Firstly, an invitation letter was sent with the questionnaire to every test flat, then two reminder letters followed within a month. Only one questionnaire was sent to every flat, using the address information and a randomly selected resident name, when 2 or more names were registered for an apartment. The tenant having birth date closest to December 1st was invited to fill in the survey copy, as a simple random selection of tenants. An internet link directing to an online form of the questionnaire was provided as well. The online form was created with a commercial survey tool Survey X-Act, following strictly the paper version of the questionnaire which is presented in the Appendix. As seen in the end of Table 5.1, 35% of the total replies were offered in the online form of the survey.

The participants of the survey provided in total 375 responses that were usable after filtering the collected data. The initial total observations were 537 (see Table 5.1). The main criteria for inclusion of subjects in the survey dataset was an age limit of 18-85 years, to have spent at least 12 months in their flat and to have normal hearing. Those who reported using hearing aids at home were filtered out. Additionally, residents of the top floors were filtered out as well, since they do not have neighbors above them to make any noise and their perception of noise annoyance and overall comfort can presumably be different. The gender distribution for the 375 final subjects includes 161 men, 207 women and 7 unreported (43% male, 55% female).

The overall response rate of the survey was 27.7%, which is a typical rate for such surveys [Ljunggren et al. 2014]. The number of collected observations is among the highest reported, but other studies have reported higher sample sizes such as 600 in [Bradley 2001], 702 in [Milford et al. 2016] and 800 replies in [Ljunggren et al. 2017]. However, previous studies did not report filtering out the responses of the highest floors as in the case of the presented study.

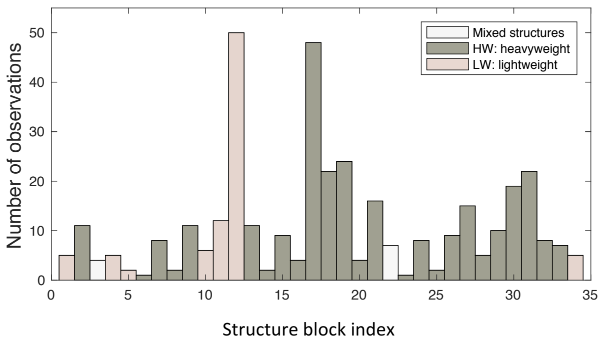


Figure 5.3 The 375 final observations grouped in the 34 structure blocks.

Summing up, acoustic data of certain Swedish structures was collected while questionnaires were sent to all building units with different address numbers. Figure 5.1 presents the distribution of the 375 observations grouped by different structure blocks. This distribution is uneven: many blocks have less than 10 observations. Furthermore, 6 blocks have 50% of the total observations (187 out of 375). This is because the distribution of buildings within structure blocks is also uneven. As presented in Figure 5.3, there are blocks with only 1 building unit while other blocks contain up to 10 units. However, this is usually the case with observations from surveys in real buildings. It is also impossible to control how many subjects may reply from every sample building.

5.3 Questionnaire design

The questionnaire of this survey, is presented in Appendix A, in Part II of the thesis. There exist a Swedish and an English version as formulated after the design process and tested with evaluation groups of acousticians within the department of the author. Professional assistance from translators was provided as well, in order to ensure the right wordings, functionality and communication.

To set up the questionnaire, past studies were utilized, as well as standardized wording for so called socio-acoustic surveys. There is a standard for such surveys which defines certain scales and vocabulary for presenting questions regarding response to noise [ISO15666 2003]. Previous research helped to define standardized wordings, the most important study being presented in [Fields et al. 2001]. This is a meta-analysis of 300 socio-acoustic surveys comparing the vocabulary used before and which words seem to represent certain questions about noise-related issues. Questionnaire items from contemporary Scandinavian and other studies were also utilized to set up this survey [Ljunggren et al. 2014, Hongisto et al. 2014, Hongisto et al. 2015, Kylliäinen et al. 2016, Milford et al. 2016, Ljunggren et al. 2017].

In the presented questionnaire, the 5-point scale ranging from 1 to 5 was used instead of the 0-10 scale. This was decided because of fewer numbers and information which could make the questionnaire look less complicated for the participants. However, there are studies supporting that there is no effect in the final response due to the orders of scale or studies suggesting a scale with 7 points is enough and the longest to be used without effect on the responses [Jamieson 2004, Carifio & Perla 2017].

The questionnaire is entitled “Research project on sound environment in residential buildings” (in Swedish: “Forskningsprojekt om ljudmiljö i bostäder”). There is a short introduction, in the the front page, inviting the residents to take part in the survey, giving some basic information about the project as well as contact details for communication. Then, in the second page, there is a long text describing the research project for the participants who demand further information. This text elaborates on how to participate, as well as the permission and the directions from the Research Ethics Board: the terms of anonymity, data privacy and safety.

There are 5 distinct modules that comprise the questionnaire which can be categorized as:

1. Situational variables	(conditions at home)
2. Characterize your sound environment	(evaluation with adjective scales)
3. Subjective annoyance	(indoor noise annoyance due to various sources)
4. Emotional assessment	(affect circumplex model – bipolar scales)
5. Personal variables	(gender, age, education, occupation, financial status)

The first module is presented in Table 5.3 and includes questions about situational variables. Question 1 concerns duration of staying at home. According to [Fields et al. 2001] and the standard [ISO 15666] for acoustic surveys, the residents taking part in a survey should have spent at least 12 months in a dwelling to be able to judge the sound environment. This question can also reveal possible differences for perception between longer and shorter durations in a flat. The other questions concern the type of dwelling (to confirm that there is only apartments in the dataset), the floor level, the size of flat and the position of the bedroom windows. They are situational variables about the structure of the flat which might be different for individual subjects within the same building. There are also questions 6 and 7 about other people at home, cotenants or children.

The second module, see Table 5.4, concerns the use of adjective scales in order to characterize the sound environment at home. This was an exploratory attempt to test some adjectives (in Swedish as presented in the survey) and potentially identify dimensions relevant to acoustic climate perception.

The third module of the questionnaire deals with noise annoyance perception and is presented in Tables 5.5-5.7. The formulation of the questions is based on previous surveys about noise annoyance in dwellings [Ljunggren et al. 2014, Hongisto et al. 2014, Hongisto et al. 2015, Kylliäinen et al. 2016, Milford et al. 2016, Ljunggren et al. 2017]. Many basic questions referring to noise annoyance due to impact sound or airborne sound related questions were used in surveys before, thus a fundament was already established. Then, for those aspects not included in surveys before, new questionnaire items with similar formulations were created.

Specifically, there are several question items which refer to annoyance due to different sources, e.g. neighbors impact sounds or outside traffic, or due to different paths, e.g. neighbors talking through walls or through the floor. There is a distinction taking place between daytime regular annoyance (Table 5.5) and noise annoyance during sleep (Table 5.7). The same noise sources were measured for annoyance during sleep to detect any differences. There are also some additional questions relevant to noise annoyance, such as 9.a and 9.b which ask residents how much they think: (i) about not disturbing their neighbors and (ii) their neighbors are disturbed by their own noise. Those question items explore the idea that somebody can be not just the receiver of noise but also the source. They are inspired by the definition of acoustic comfort [Rindel 2002] as analyzed in Chapter 3.

Table 5.3 The first questionnaire module concerning situational variables.

Firstly, we would like to ask you a few questions about your home.	
1. How long have you lived in your home?	a. …… (years)
2. What type of building do you live in?	1. Apartment building
	2. Terraced house
	3. Detached house
3. On what floor do you live?	1. Ground floor
	2. Top floor
	3. Other ......
4. What is the size of your home?	………. m^2
5. Does your bedroom window face a:	1. Local street
	2. Main road
	3. Motorway
	4. Train/tram tracks
	5. Yard/park
	6. Shops/other activity
6. How many people, including you, are currently living in your home?	…...
7. Do you have children living with you on a regular basis?	a. 1. No 2. Yes
	b. Age/s …………

Table 5.4 The second questionnaire module about characterization of home sound environment.

The following questions concern the sound environment in your home.

8. Thinking about the last 12 months, when you are here at home, how would you describe the sound quality in your home when all windows and doors are shut? Answer each one by circling the number that most accurately describes your situation. Don't spend too much time on each question – we are looking for your immediate reaction.

	Not at all	**Slightly**	**Moderately**	**Very**	**Extremely**
a. Quiet	1	2	3	4	5
b. Soft	1	2	3	4	5
c. Muffled	1	2	3	4	5
d. Loud	1	2	3	4	5
e. Hard	1	2	3	4	5
f. Pleasant	1	2	3	4	5
g. Sharp	1	2	3	4	5
h. Comfortable	1	2	3	4	5
i. Noisy	1	2	3	4	5
j. Rattling	1	2	3	4	5
k. Buzzing	1	2	3	4	5
l. Unpleasant	1	2	3	4	5
m. Echoing	1	2	3	4	5
n. Calm	1	2	3	4	5
o. Grinding	1	2	3	4	5
p. Not soundproof	1	2	3	4	5

Further comments: …….

Table 5.5 The third questionnaire module about noise annoyance from various sources – Part 1: General annoyance during the day.

9. Thinking about the last 12 months, when you are here at home…	**Not at all**	**Slightly**	**Moderately**	**Very**	**Extremely**
a. How much do you think about not disturbing your neighbors when you e.g. play music, close doors, or walk around?	1	2	3	4	5
b. How disturbed/bothered do you think your neighbors are from the noise you make?	1	2	3	4	5
The following questions concern specific sources of sound that you may hear when you are at home. 10. Thinking about the last 12 months, when you are here at home, with the windows and doors shut, how much disturbed are you by:					
a. **Noise from machines or appliances inside the building?** (Refrigerator, freezer, washer, dryer, lift, AC, ventilation, water pipes, flushing toilets)	1	2	3	4	5
b. **Low-frequency noise** from a neighbor's sound system, TV or computer, coming through the walls?	1	2	3	4	5
c. **Low-frequency noise** from a neighbor's sound system, TV or computer, coming through the floor or ceiling?	1	2	3	4	5
d. **Sound of neighbors talking**, coming through the walls?	1	2	3	4	5
e. **Sound of neighbors talking**, coming through the floor or ceiling?	1	2	3	4	5
f. **Sound of neighbors walking**, slamming doors and dropping things, thuds from children playing, coming through the floor or ceiling?	1	2	3	4	5
g. **Sound of walking** in shared spaces of the building (staircase, hallway, etc.)?	1	2	3	4	5
h. **Low-frequency noise** (rumbling, muffled sound) from **outside sources such as music, traffic and ventilation?**	1	2	3	4	5

Additional control questions were included for the subject of noise annoyance during sleep as well. For instance, Table 5.6, presents two questions about sleeping conditions of the individual subjects, to explore if somebody's sleep patterns are normal or not. If disrupted sleeping is reported, this might affect the perception during sleep and may indicate that somebody's problem can be for instance insomnia instead of noise annoyance. Then Table 5.7 includes questions about moving away due to noise problems or about noise types that were not addressed in the survey.

Table 5.6 The third questionnaire module about noise annoyance from various sources – Part 2: Self-reporting sleeping situation.

The following questions concern your sleep					
	Very good	Fairly good	Neither good nor bad	Fairly bad	Very bad
11. How would you rate your normal quality of sleep?	1	2	3	4	5
	Not at all	1–2 times/week	3–4 times/week	5–6 times/week	Every night
12. In a regular week, how often does noise disturb your sleep?	1	2	3	4	5
If you ticked the box "3–4 times/week" or more, describe the noise that is disturbing you:					

Table 5.7 The third questionnaire module about noise annoyance from various sources – Part 3: Night time annoyance during sleep.

The following questions concern specific sources of sound that you may hear when you are at home. **13. Thinking about the last 12 months, when you are here at home with the windows and doors shut, how much is your sleep disturbed by:**	**Not at all**	**Slightly**	**Moderately**	**Very**	**Extremely**
a. **Noise from machines or appliances inside the building?** (Refrigerator, freezer, washer, dryer, lift, AC, ventilation, water pipes, flushing toilets)	1	2	3	4	5
b. **Low-frequency noise** from a neighbor's sound system, TV or computer?	1	2	3	4	5
c. **Sound of neighbors talking**?	1	2	3	4	5
d. **Sound of neighbors walking**, slamming doors and dropping things, thuds from children playing?	1	2	3	4	5
e. **Sound of walking in shared spaces** of the building (staircase, hallway, etc.)?	1	2	3	4	5
f. **Low-frequency noise** (rumbling, muffled sound) from outside sources such as music, traffic and ventilation?	1	2	3	4	5
14. Are you considering moving from your home due to noise pollution? 1. No / 2. Yes					
15. Is there any other disturbing source of noise in or close to your home that we have not addressed? 1. No / 2. Yes If so, please indicate the level of disturbance:	1	2	3	4	5
If you ticked the box for "Moderately" or higher, please describe the source: ……					

The fourth module in the survey's questionnaire deals with emotional response to sound environment at home, see Table 5.8. This module is evolved based on the circumplex model of affect, a construct developed in Psychology research [Russel 1980]. A Swedish study was presented later in [Västfjäll et al. 2000], using the affect circumplex for the emotional evaluation of subjects towards an environment. The question items 16.a-16.l are taken directly from that study since they were designed for Swedish wording and validated in wide experiments. Additionally, there is question 17 which is about satisfaction with the acoustic climate at home, since similar questions were included in previous socio-acoustic surveys [Hongisto et al. 2015].

Table 5.8 The fourth questionnaire module about emotional reactions towards the home acoustic environment.

16. Different environments can affect the way we feel and our well-being. What effect does your home have on you?

Answer each one by circling the number that most accurately describes the way you feel when you come home*. Don't spend too much time on each question – we are looking for your immediate reaction. These are scales of opposites, so if you feel more drowsy than alert, circle either number 1 or 2 on the scale. If you are right in between, circle number 3.*

a. Sleepy	1	2	3	4	5	Awake
b. Displeased	1	2	3	4	5	Pleased
c. Bored	1	2	3	4	5	Interested
d. Tense	1	2	3	4	5	Serene
e. Passive	1	2	3	4	5	Active
f. Sad	1	2	3	4	5	Glad
g. Indifferent	1	2	3	4	5	Engaged
h. Anxious	1	2	3	4	5	Calm
i. Dull	1	2	3	4	5	Peppy
j. Depressed	1	2	3	4	5	Happy
k. Pessimistic	1	2	3	4	5	Optimistic
l. Nervous	1	2	3	4	5	Relaxed

17. How pleased are you with the sound environment in your home?

Very pleased	Fairly pleased	Neither pleased nor displeased	Fairly displeased	Very displeased
1	2	3	4	5

Finally, the fifth questionnaire module concerns personal variables which might need to be controlled in the data analysis. It is presented in Tables 5.9 and 5.10. The question items refer to demographic characteristics such as gender, age, ethnicity, occupation, education and financial status. Some items refer to personal traits such as self-reported health, noise sensitivity and use of hearing aids, in order to assess if participants have normal hearing abilities and health condition.

The questions about noise sensitivity and health are considered necessary since the subjects cannot be tested for normal hearing as would be the case during a laboratory experiment. However, those two variables have been connected to noise annoyance in medical studies. Noise sensitivity was associated to noise annoyance and the health status of subjects was found to affect noise sensitivity [Schreckenberg et al. 2010]. Noise sensitivity was also explored in previous field acoustic studies [Fields 1993, Hongisto et al. 2015, Park et al. 2019] and in one of them it was found to significantly influence noise annoyance [Park et al. 2019]. Also, it is important to clarify that it is a self-reported sensitivity question while there are instruments such as the Weinstein noise sensitivity scale to properly measure sensitivity of subjects [Weinstein 1980].

Table 5.9 The fifth questionnaire module about personal variables – Part 1.

Finally, a few questions about you:	
18. Are you:	1. Man / 2. Woman
19. What year were you born?	……
20. How would you describe your sensitivity to sound?	1. Not at all sensitive 2. Somewhat sensitive 3. Fairly sensitive 4. Very sensitive 5. Extremely sensitive
21. Do you regularly use hearing aids at home?	1. No / 2. Yes
22. In the last 12 months, how would you describe your health?	1. Very good 2. Good 3. Neither good nor bad 4. Bad 5. Very bad

Table 5.10 The fifth questionnaire module about personal variables – Part 2.

The following questions are to determine whether the participants in the survey are representative of society at large.	
23. Are you:	1. Single 2. In a cohabiting/ live apart relationship 3. Married 4. Divorced 5. Widow/er 6. Other
24. Were you born in Sweden?	1. No / 2. Yes
25. If No, how long have you lived in Sweden?	…… years
26. What is your highest completed level of education?	1. Elementary/primary school 2. Upper secondary school/high school 3. University
27. What is your current occupation?	1. Student 2. Stay at home parent /parental leave 3. On sick leave 4. On a leave of absence 5. Unemployed 6. Employed (currently working) 7. Other
28. What is your household's total monthly income before tax?	1. SEK 0–14 999/month 2. SEK 15000–29 999/month 3. SEK 30 000–44 999/month 4. SEK 45 000– 59 999/month 5. SEK 60 000 or more/month
29. Would you recommend your place of residence to someone else? Further comments (optional): ……	1. No / 2. Yes
30. May we contact you to conduct possible sound level measurements?	1. No / 2. Yes

6. Preview of research publications

A summary of the appended publications is presented in this chapter. For every manuscript the author's contribution is mentioned in terms of scientific research as well as writing the paper. Additional publications are presented as well: papers that are not appended as part of this thesis but they are relevant to the research conducted earlier or during this PhD project work.

6.1 Summary of the appended papers

6.1.1 Paper A

Review of acoustic comfort evaluation in dwellings – Part I: Associations of acoustic field data to subjective responses from building surveys.

Vardaxis N.-G., Bard D., Persson Waye K.

Building Acoustics, 25(2), 2018, 151–170.

Summary: in this paper, a literature review was attempted regarding acoustic studies dealing with investigation of acoustic comfort. The first part of the review is presented in this manuscript which concerns acoustic surveys in buildings, i.e. field studies that dealt with acoustic measurements in apartments and the noise perception of residents in their actual living environment. The statistical association of acoustic data to subjective responses is of interest, in order to develop prediction models for human perception. That topic is very close to the objectives of this thesis. Most reviewed studies investigate subjective noise annoyance while few others explore also satisfaction of the building occupants. All studies utilize in situ standardized acoustic measurements. The main conclusion is that impact noise from neighbors is the most serious disturbance in dwellings and that impact sound levels, as well as airborne sound reduction levels, can correlate well in many cases with the subjective annoyance. To improve that correlation, some studies explored different acoustic descriptors with correction spectra that include low frequencies, lower than 100Hz which is the ISO standard limit; they reported higher correlation of residents' annoyance when lower frequencies are included in the descriptors. The studies suggest differences in subjective noise perception for residents of lightweight and heavyweight building structures. The statistical evaluation of results in the studies was found insufficient in many cases.

Contributions: for this manuscript, the author conducted the review, collection, evaluation and processing of the research papers, and the final composition of the manuscript. Delphine Bard and Kerstin Persson Waye offered scientific insights, comments and supplementary proofreading.

6.1.2 Paper B

Review of acoustic comfort evaluation in dwellings – Part II: impact sound data associated with subjective responses in laboratory tests.

Vardaxis N.-G., Bard D.

Building Acoustics, 25(2), 2018, 171–192.

Summary: in this paper, a continuation of the literature review is presented. This second part is focused on laboratory studies concerning impact sound measurements on test floors and their association to human perception. The lab experiments confirm that the inclusion of low frequencies for impact sound descriptors improves the correlation to subjective noise annoyance. They also suggest that there are some differences in human perception due to the use of different impact sources; standardized tapping machine measurements associate well with overall noise annoyance but not so well with annoyance due to human walking noise types. For footstep noise annoyance, the use of impact ball is suggested in some studies. Other psychoacoustic parameters (e.g. loudness levels) and temporal characteristics (e.g. decay, modulation) were used in the lab studies to predict successfully the subjective annoyance ratings.

Contributions: for this manuscript, the author conducted the review, collection, evaluation and processing of the research papers, and the final composition of the manuscript. Delphine Bard offered scientific insights, comments and supplementary proofreading.

6.1.3 Paper C

Review of acoustic comfort evaluation in dwellings – Part III: Airborne sound data associated with subjective responses in laboratory tests.

Vardaxis N.-G., Bard D.

Building Acoustics, 25(4), 2018, 289-305.

Summary: the last of the literature review is presented in this manuscript. This third part is focused on laboratory studies which utilize airborne sound related data such as acoustic descriptors (derived from measurements) or synthesized test sounds filtered with airborne sound reduction spectra. The acoustic data in the reviewed studies concern mostly horizontal sound transmission between wall components. The association of those data to subjective noise annoyance or loudness responses is investigated in lab experiments. Some studies conclude again a difference on the perception of residents for the cases of heavyweight and lightweight walls. Most airborne sound lab results support that inclusion of low frequencies below 100Hz in calculation of acoustic descriptors does not improve the correlation to subjective responses. Another finding is that different airborne sound descriptors correlate better to subjective ratings of various noise types, e.g. transmission of music or speech. The overall conclusions of this review are not clear towards certain results.

Contributions: for this manuscript, the author conducted the review, collection, evaluation and processing of the research papers, and the final composition of the manuscript. Delphine Bard offered scientific insights, comments and supplementary proofreading.

6.1.4 Paper D

Acoustic Comfort Investigation in Residential Timber Buildings in Sweden.

Bard D., Vardaxis N.-G., Sondergaard E.

Journal of Sustainable Architecture and Civil Engineering, 2019.

Summary: this manuscript lays out the initial results of noise annoyance related data acquired from the acoustic survey in buildings during this PhD project. The focus of this paper is on the results of the thesis regarding lightweight wooden structures (LW) specifically; but a comparison is presented as well for the subjective annoyance of residents in heavyweight concrete structures (HW). An overall high level of acoustic comfort is concluded for the LW residents and higher than the HW occupants. Noise types such as: impact noise from neighbors (walking, jumping), installation noise in the building and outside low frequency noise sources, were reported as the highest disturbances ranked in that sequence. There are considerable limitations due to small sample size of LW buildings and the lack of control for the age of the subjects in this study part.

Contributions: in this study N.-G. Vardaxis conducted data collection, analysis and writing of the paper. Delphine Bard contributed with the data collection, writing and proofreading. Elin Sondergaard offered scientific insights and comments.

6.1.5 Paper E

Evaluation of noise annoyance in apartment buildings: associations of acoustic data to subjective responses.

Vardaxis N.-G., Bard D.

Journal of Building and Environment, 2019. (Submitted June 2019)

Summary: this manuscript presents an attempt to utilize the subjective noise annoyance data of the acoustic survey for the development of prediction models. The statistical association of the acoustic descriptors to self-reported annoyance is investigated: all noise annoyance responses of the survey were tested against all acoustic descriptors. The best associated variables were used for the development of univariate or multivariate statistical models that explain the noise annoyance of residents, for the individual cases of airborne sound or impact sound annoyance. Additional parameters were tested too for the formulation of multivariate models, such as the number of flats in a building and the size of an apartment; those parameters were found significant to predict noise annoyance in combination with the relevant acoustic descriptors of airborne or impact sound.

Contributions: for this paper N.-G. Vardaxis conducted the data collection, statistical analyses and wrote most of the manuscript. Delphine Bard contributed with scientific insights, comments and supplementary proofreading.

6.1.6 Paper F

Acoustic comfort assessment in heavyweight residential buildings: acoustic data associated to subjective responses.

Vardaxis N.-G., Bard D.

ICA 2019, Aachen, Germany, September 9-13, 2019.

Summary: in this manuscript a summary of results of the acoustic survey is provided and a deep analysis for acoustic comfort is performed. A psychological model based on principal components analysis is utilized to evaluate the overall acoustic comfort in the sample buildings. Associations of the comfort perception to other study variables such as noise annoyance, satisfaction, building parameters and structure type are explored. A statistical model for the prediction of subjective acoustic comfort responses is developed, based on the two emotional dimensions, valence and activation. A novel scale for evaluation of acoustic comfort in apartments is suggested based on the comfort prediction models. Finally, a new indicator is suggested as well, as a single number quantity (SNQ) which could be used for acoustic comfort characterization.

Contributions: for this paper N.-G. Vardaxis conducted the data collection, statistical analyses and wrote most of the manuscript. Delphine Bard contributed with scientific insights, comments and supplementary proofreading.

6.1.7 Appendix A

A.1 Questionnaire in English

A.2 Questionnaire in Swedish

Summary: in this attachments there are the questionnaire versions in English and Swedish in their final formulation. The Swedish version was used during the acoustic survey presented in this thesis project. The English version was developed first and then it was translated to Swedish. Then it was translated back to Swedish with the assistance of professional translators.

6.2 Related publications not included in this thesis

Investigation of the acoustic properties of facade elements - Selected study cases of Swedish building constructions.

Bard D., Vardaxis N.-G., Negreira J.,

Report TVBA-3132, Division of Engineering Acoustics, Lund University, Sweden, 2016.

7. Conclusions

The concept of acoustic comfort in apartments remains complex although this study attempts to set up a fundament for analysis. A multidimensional approach was developed in this thesis, investigating parameters relevant to indoor acoustic comfort. A toolset of methods is provided for analysis and prediction of subjective acoustic comfort, a toolset which can be used by engineers and designers involved in architectural and construction planning.

7.1 Principal outcome

The outcome of this thesis is presented according to the objectives expressed in the first chapter:

i. To set up a background for the concept of acoustic comfort

A wide review of studies relevant to acoustic comfort studies is published in Papers A, B and C. This is the first literature review of its kind, meaning that no such reviews were published before. The information regarding acoustic comfort surveys were dispersed in noise annoyance based studies or laboratory experiments focused on noise annoyance and performance of building elements. It was an innovation to collect and organize them in a review. Paper A is the manuscript connected the most to the subject of this thesis, since it reviews field acoustic surveys while Papers B and C deal with laboratory studies.

Paper A reports the only definition of acoustic comfort. The analyzed studies in Paper A deal with noise annoyance of residents in apartments and associate subjective annoyance to acoustic descriptors. In most studies high linear correlations were demonstrated between self-reported annoyance and standardized airborne or impact sound indices. Some of the studies focused on lightweight wooden structures and reported that impact sound descriptors with extended frequency spectra down to 50 Hz, or even 20 Hz, correlated better with subjective annoyance. Alternative correction spectra for the standardized impact sound descriptors were suggested in some studies. The issue of including low frequencies in measurements and descriptors was clearly raised and supported for the cases of lightweight structures.

Papers B and C show similar results from laboratory experiments which also explore more variables as explanatory for subjective annoyance and loudness perception. The results of associating noise annoyance to acoustic descriptors were a bit different in laboratory studies. In some cases, there were high correlations reported again. But in some other studies subjective annoyance correlated well with certain descriptors and correlated insufficiently with some others, depending on the case. For instance, different airborne sound descriptors were suggested to represent annoyance to road traffic noise, speech and music.

The above cases show the only approaches taken previously on acoustic comfort but they concern mostly noise annoyance investigations. This indicates the importance of wider studies such as the one presented in this thesis. An attempt to explore acoustic comfort beyond noise annoyance was performed in this project, as reflected in the survey's questionnaire design. Two certain question modules regarding subjective characterization of sound environment and the emotional reactions of residents to sound environment at home were developed to investigate more dimensions that may help to define and evaluate the sense of comfort.

ii. To describe how the residents perceive noise, acoustic qualities and comfort at home.

The subjective noise annoyance of residents due to different sources in apartments was investigated. Impact noise types from neighbors, walking, stepping or dropping things on the floor were reported to be the most disturbing. Installations noise in the building (ventilation, water pipes) was the second biggest annoyance source. Low-frequency noise types from outside the building was the third biggest annoyance. Then neighbors' noise in common spaces (corridors, staircase) were found to disturb a lot too. Additionally, residents reported that they think a lot about not producing sounds to disturb their neighbors: 47% reported to consider that moderately to extremely. In the same time, most residents consider that their neighbors are not disturbed by noise they make in overall. Those results are presented in Papers D and E.

When asked about noise sources not included in the questionnaire, some residents mentioned the noise from construction sites next to their buildings. This is a parameter which cannot be controlled or studied further. It was reported though as a temporary nuisance in the survey. No other additional noise source was mentioned in more than 3 questionnaire replies.

When asked about their emotional reactions towards the sound environment in their flats, the residents offered a positive response in most cases. The total evaluation indicated a high sense of acoustic comfort in the apartments of this study, as presented in Paper F. The residents also reported a high degree of satisfaction with their sound environment at home. Such results seem reasonable since most of the test buildings comply with the current minimum acoustic requirements in Sweden [Boverket 2016].

iii. To investigate the association between acoustic data and self-reported responses.

Important statistical associations were established for certain variables. The acoustic descriptors for airborne sound reduction and impact sound levels, $D_{nT,w,100}$=52 dB and $L'_{nT,w,100}$=56 dB respectively, were associated best to self-reported responses of noise annoyance, satisfaction and emotional reactions to the home acoustic environment. Other parameters associated to those self-reported responses were the size of the flat, the number of flats in the building, the number of tenants in a flat and the presence of children at home.

The effect of certain frequencies on noise annoyance was investigated too in Paper E. Frequency bands between 400-2500 Hz in standardized level difference curves D_{nT} were found to influence higher noise annoyance due to airborne sound. For subjective annoyance relevant to impact sound, the highest effect was observed for the frequency bands between 160-400 Hz of the measurement curves L'_{nT}. In general, noise annoyance was also highly associated to bands above 800 Hz but not that high for bands below 125 Hz, which was unexpected. A comparison of acoustic descriptors with correction spectra from 100 Hz ($D_{nT,w,100}$, $L'_{nT,w,100}$) and from 50 Hz ($D_{nT,w,50}$, $L'_{nT,w,50}$) took place as well. Descriptors from 100 Hz associated better in most cases and this was unexpected too. As mentioned before, recent studies supported the inclusion of low frequencies for better associations with noise annoyance in the case of lightweight structures. However, the dataset of this survey is dominated by heavyweight concrete buildings.

iv. To formulate acoustic comfort models and a descriptor for comfort in apartments.

Based on the aforementioned associations, statistical models were developed for the prediction of subjective responses of noise annoyance and presented in Paper E. Dose-response curves based on regression models are presented in Paper E. The descriptors $D_{nT,w,100}$ and $L'_{nT,w,100}$ were found to predict noise annoyance due to neighbors talking and low-frequency noise from neighbors respectively. The number of flats in a building was found to be an additional predictor in models with both acoustic descriptors. Additionally, the size of a flat became a significant variable only with the airborne sound descriptor $D_{nT,w,100}$ in a model for noise annoyance prediction.

To develop a model for acoustic comfort in apartments, the residents' emotional reactions to home sound environment were utilized. Two underlying dimensions were identified according to the analysis of the circumplex model of affect [Västfjäll et al. 2000]: pleasantness and activation. Then prediction models for the two dimensions were evolved, based on similar variables as for the noise annoyance models

A new scale was created to represent evaluation of acoustic comfort based on the two underlying dimensions. Finally, a new SNQ, a simple descriptor of acoustic comfort is presented too, see Paper F. However, the acoustic comfort modelling process was successful only for the case of heavyweight concrete buildings in the dataset. The results of principal components analysis were not strong enough to formulate a similar model and descriptor for lightweight structures.

v. To establish a reliable procedure for engineers to predict acoustic comfort in flats.

The statistical methodology used and the acoustic comfort scale presented as the final outcome comprise a tool that can be used with ease for acoustic comfort evaluation and classification in apartments. Acousticians, engineers and designers can now make use of the suggested AC_{index} when they know the measured or estimated acoustic descriptor $L'_{nT,w,100}$ of a structure. Also, using known acoustic and construction parameters, they can utilize the provided prediction models for noise annoyance and acoustic comfort and evolve them further.

They can also classify apartments according to the four suggested classes, ranging from AC-1 to AC-4, in order to denote that a certain house provides “Very good”, “Good” or “Acceptable” or “No acoustic comfort” conditions. Last but not least, they can set targets for a certain comfort class from an early design stage. Hence they can control and increase the acoustic quality of the dwellings to be constructed.

7.2 Novel contributions

Some contributions of the thesis comprise novelties within the research field of acoustics. Since this is the first PhD thesis attempting a multidimensional approach towards acoustic comfort in apartments, many conclusions go further than previous knowledge, methods and tools used in building acoustics.

7.2.1 New approaches

The literature review which was conducted and presented in Papers A, B and C was the first organized review of studies regarding acoustic comfort in situ (in real apartments) and laboratory studies. No other complete review was presented before in any paper in the field of acoustics. It is not a systematic review, meaning a review focused on a certain research question, as the term is used in medical sciences for instance. However, it is a review process during which dispersed research information was collected, organized, evaluated for research accuracy using the Bradford Hill's criteria [Höfler 2005] and some new information was synthesized.

During this thesis, a psychological instrument was utilized to evaluate acoustic comfort, based on the residents' emotional reactions to their living environment. This construct has been previously validated in laboratory tests and was used in the presented socio-acoustic survey for assessment of acoustic comfort in the field, in real apartment buildings. Only noise annoyance scales and statistical regression have been tested in previous studies, especially field surveys.

7.2.2. New indicators

A novel indicator was developed and suggested, the AC_{index} based on a psychological tool, the circumplex model of affect, analyzed with PCA. This means also the derivation of a new scale according to the range of values for the AC_{index}. The application of the affect circumplex and the AC_{index} can be used in future surveys to evaluate acoustic comfort in apartments. With more surveys the usability of the suggested index can be tested further. Overall, a SNQ is suggested as a simple numerical descriptor, which can indicate acoustic comfort in a flat and can be used for classification of existing dwellings.

Hence, a new classification system was suggested to assess acoustic comfort in apartments. Classification is based on the range of the AC_{index}. Finally, 4 classes of acoustic comfort were suggested as "Very good", "Good", "Acceptable" and "No acoustic comfort", which are entitled AC-1, AC-2, AC-3 and AC-4 respectively [Paper F].

7.3 Future work proposal

Since the concept of acoustic comfort is not sufficiently defined and explored in past research, a more complete approach was initiated by this PhD project. The methods and tools used during the presented study provide initial results which may find useful applications. However, further development has to be done in certain parts related to the limitations of this study and the methods utilized. Specifically, suggestions for a continuation of this study (or similar ones) would include:

- Further data collection using wider acoustic surveys with a common framework would be necessary for ultimate conclusions. The total sample size of combined studies using the same research questions could be beneficiary for solid statistical inference.

- Combination of field surveys and laboratory studies with common objectives tested in apartments but also in a lab setup. This can be a way to identify certain differences in outcomes when conducting surveys in different setups. It may help to specify factors that affect the results.
- Randomized controlled trials would be essential to test the suggested acoustic comfort scale and indicator. Laboratory tests could take place where different acoustic conditions, generated in a lab setup could be evaluated by various participants using the suggested scale. This way the functionality of the new scale and indicator could be tested better and improvements might arise.

Bibliography

Abbaszadeh S., Zagreus L., Lehrer D., Huizenga C., Occupant satisfaction with indoor environmental quality in green buildings, Healthy Buildings 2006 (3), 365-370.

Agresti A., An Introduction to Categorical Data Analysis, 2nd Edition, Wiley, 2007.

Aletta F., Axelsson Ö., Kang J., Dimensions underlying the perceived similarity of acoustic environments, Front. Psychol 8:1162, 2017.

Aletta F., Kang J., Towards an Urban Vibrancy Model: A Soundscape Approach, Int. J. Environ. Res. Public Health 2018(15:1712), 2018.

ASTM E413 "Classification for Rating Sound Insulation", American Society For Testing and Materials International, West Conshohocken, PA, USA, 1999.

Axelsson Ö., Nilsson M.E., Berglund B., A principal components model of soundscape perception, J. Acoust. Soc. Am. 128(5), 2010.

Bland J., Altman D., Statistics notes: Cronbach's alpha, British Medical Journal (1997) 314:572, 1997.

Bodlund K., Alternative reference curves for evaluation of the impact sound insulation between dwellings, J. Sound and Vibration 102, 381-402 (1985).

Bradley J.S., Acoustical Measurements in Some Canadian Homes, Canadian Acoustics 14(4) (1986).

Bradley J.S., Deriving acceptable values for party wall insulation from survey results, Proceedings Inter-noise 2001, Hague, Netherlands (2001).

C. Simmons, Chapter 6: Developing a uniform questionnaire for socio-acoustic surveys in residential buildings. In: Building acoustics throughout Europe, Vol. 1: Towards a common framework in building acoustics throughout Europe, 102-124 (2013).

Cambridge Dictionary (2019), internet website: https://dictionary.cambridge.org/dictionary/english/comfort, search on May 5th, 2019.

Campbell M.J., Machin D., Walters S.J., Medical Statistics: A Textbook for the Health Sciences, Wiley, 4th edition, 2007.

Carifio J., Perla R.J., "Ten Common Misunderstandings, Misconceptions, Persistent Myths and Urban Legends about Likert Scales and Likert Response Formats and their Antidotes", Journal of Social Sciences 3 (3), 2017, 106-116.

Chevret P., Chatillon J., Acoustic discomfort for tertiary-sector employees: issues and means of action for prevention, Acoustics in Practice 2015(5).

Fields J.M., De Jong R.G., Gjestland T., Flindell I.H., Job R.F.S., Kurra S., Lercher P., Vallet M., Yano T., Guski R., Felscher-Suhr U., Schumer R., Standardized general-purpose noise reaction questions for community noise surveys: research and a recommendation; Community response to noise team of ICBEN, J. Sound and Vibration 242(4):641-679, 2001.

Fields J.M., Effect of personal and situational variables on noise annoyance in residential areas. J. Acoust. Soc. Am. (1993) 93:2753-63, 1993.

Forssén, J., Kropp, W., Brunskog, J., Ljunggren, S., Bard, D., Sandberg, G., Ljunggren F., Ågren, A., Hallström, O., Dybro, H., Larsson, K., Tillberg, K., Sjökvist, L.G., Östman, B., Hagberg, K., Bolmsvik, A., Olsson, A., Ekstrand, C.G., Johansson, M., Acoustics in wooden buildings. State of the art 2008. Vinnova project 2007-01653, Technical Research Institute of Sweden. Report 2008:16, Stockholm, Sweden, 2018.

Gover B. N., Bradley J., Schoenwald S., Zeitler B., Subjective Ranking of Footstep and Low-Frequency Impact Sounds on Lightweight Wood-Framed Floor Assemblies, Proceedings Forum Acusticum 2011, Aalborg, Denmark, 2011.

Gover B. N., Bradley J.S., Zeitler B., Schoenwald S., Objective and Subjective Assessment of Lightweight Wood-Framed Floor Assemblies in Response to Footstep and Low-Frequency Impact Sounds, Proceedings Inter-Noise 2011, Osaka, Japan, 2011.

Guigou-Carter C., Balanant N., Villenave M., “Acoustic comfort evaluation in lightweight wood-based buildings”, Proceedings Forum Acusticum, Krakow, Poland (2014).

Hagberg K., Bard D., “Low frequency sound transmission in multifamily wooden houses” Inter-noise 2014, Melbourne, Australia (2014).

Hagberg K., Evaluating field measurements of impact sound, J. Building Acoustics 2010(17), 105-128 (2010).

Hagberg K., Ljudkrav metod av ISO/DIS 717, NKB Committee and Work Reports 1996:02, Nordic Committee on building Regulations, Monila Oy, Helsinki (1997).

Hagberg K., Management of acoustics in lightweight structures, Doctoral Thesis, Engineering Acoustics, LTH, Lund University, Lund, Sweden, 2018.

Höfler M., The Bradford Hill considerations on causality: a counterfactual perspective, Emerging Themes in Epidemiology 2005, 2-11 (2005).

Hongisto V., Mäkilä M., Suokas M., Satisfaction with sound insulation in residential dwellings – The effect of wall construction, J. Building Environment 86(2015), 309-320 (2015).

Hongisto V., Oliva D., Keränen J., Subjective and Objective Rating of Airborne Sound Insulation – Living Sounds, Acta Acustica united with Acustica, Vol. 100(2014):848-864, 2014.

Høsøien C.O., Rindel J. H., Løvstad A., Klæboe R., “Impact sound insulation and perceived sound quality”, Proceedings Inter-noise 2016, Hamburg, Germany (2016).

Huber-Carol C., Balakrishnan N., Nikulin M., Mesbah M., Goodness-of-Fit Tests and Model Validity, Springer, 2002.

Hveem S., Homb A., Hagberg K., Rindel J. H., Low-frequency Footfall Noise in Multi-storey Timber Frame Buildings. NKB Committee and Work Reports 1996:12 E, NKB Nordic Committee on building Regulations, Monila Oy, Helsinki (1997).

ISO 12913-1:2014 "Acoustics – Soundscape – Part 1: Definition and conceptual framework." (International Organization for Standardization, Geneva, Switzerland), 2014.

ISO 140 "Acoustics – Measurement of sound insulation in buildings and of building elements, – 4:Field measurements of airborne sound insulation between rooms, – 7:Field measurements of impact sound insulation of building elements" (International Organization for Standardization, Geneva, Switzerland, 1998).

ISO 15666 "Acoustics - Assessment of noise annoyance by means of social and socio-acoustic surveys", International Organization for Standardization, Geneva, Switzerland (2003).

ISO 16283 "Field measurement of sound insulation in buildings and of building elements, - Part 1: Airborne sound insulation, - Part 2: Impact sound insulation" (International Organization for Standardization, Geneva, Switzerland, 2014).

ISO 717 "Acoustics – Rating of sound insulation in buildings and of buildings elements. – 1: Airborne sound insulation, – 2:Impact sound insulation" (International Organization for Standardization, Geneva, Switzerland, 1996).

ISO EN 12354 "Building Acoustics – estimation of acoustic performance of buildings from the performance of elements, – Part 1: Airborne sound insulation between rooms, – Part 2 :Impact sound insulation between rooms" (International Organization for Standardization, Geneva, Switzerland, 2017).

Jackman S., pscl: Classes and methods for R. Developed in the Political Science Computational Laboratory, Stanford University. Department of Political Science, Stanford University, R package version 1.03.5, 2017.

Jamieson S., "Likert scales: how to (ab)use them.", Med. Educ. (2004) 38:12, 1217-8, 2004.

Jeon J. Y., Lee P. J., Kim J. H., Yoo S. Y., Subjective evaluation of heavy-weight floor impact sounds in relation to spatial characteristics, J. Acoust. Soc. Am. 125(5): 2987-94, May, 2009.

Jeon J. Y., Oh S. M, Psychoacoustical evaluation of heavyweight floor impact sounds in apartment buildings, Proceedings Inter-Noise 2014, Melbourne, Australia, 2014.

Jeon J. Y., Sato S., Annoyance caused by heavyweight floor impact sounds in relation to the autocorrelation function and sound quality metrics, J. Sound Vib., Vol.311(2008) 767-785, 2008.

Jeon J.Y., Jeong J.H., Vorländer M., Thaden R., Evaluation of floor impact sound insulation in reinforced concrete buildings, Acta Acustica united with Acustica, Vol. 90(2004) 313-318, 2004.

Jeon J.Y., Ryu J.K., Jeong J. H., Tachibana H., Review of impact ball in evaluating floor impact sound, Acta Acustica united with Acustica, Vol. 92(2006) 777-786, 2006.

JIS A 1418-2:2000 “Acoustic – Measurement of floor impact sound insulation of buildings – Part 2: Method using standard heavy impact sources”, Japanese Industrial Standards Committee, Tokyo, Japan (2000).

Johnson R.A., Wichern D.W., Applied Multivariate Statistical Analysis, Pearson New International Edition, 2013.

Kim J. H., Ryu J. K., Jeon J. Y., Effect of temporal decay on perception of heavy-weight floor impact sounds, J. Acoust. Soc. Am. 134(4): 2730-38, October, 2013.

Kleiner M., Audio Technology and Acoustics, Division of Applied Acoustics, Chalmers University of Technology, 2nd Edition, Gothenburg, Sweden, 2008.

Kuttruff H., Acoustics: An introduction, CRC Press, 1st edition, 2006.

Kylliäinen M., Hongisto V., Oliva D., Rekola L., A laboratory listening experiment on subjective and objective rating of impact sound insulation of concrete floors, Proceedings Inter-Noise 2016, Hamburg, Germany, 2016.

Kylliäinen M., Hongisto V., Oliva D., Rekola L., Subjective and Objective Rating of Impact Sound Insulation of a Concrete Floor with Various Coverings, Acta Acustica united with Acustica, Vol. 103(2017) 236-250, 2017.

Lee P. J., Kim J. H., Jeon J. Y., Psychoacoustical Characteristics of Impact Ball Sounds on Concrete Floors, Acta Acustica united with Acustica, Vol. 95(2009) 707-717, 2009.

Ljunggren F., Simmons C., Hagberg K., “Correlation between sound insulation and occupants’ perception – Proposal of alternative single number rating of impact sound”, Applied Acoustics 85, 57-68 (2014).

Ljunggren F., Simmons C., Hagberg K., “Findings from the AkuLite project: Correlation between measured vibro-acoustic parameters and subjective perception in lightweight buildings” Proceedings Inter-noise 2013, Innsbruck, Austria (2013).

Ljunggren F., Simmons C., Öqvist R., “Correlation between sound insulation and occupants’ perception – Proposal of alternative single number rating of impact sound - Part II”, Applied Acoustics 123, 143-151 (2017).

Ljunggren F., Simmons C., Öqvist R., “Evaluation of impact sound insulation from 20Hz”, Proceedings 24th International Congress on Sound and Vibration, ICSV24, London, United Kingdom (2017).

Miedema H. M. E., Vos H., Demographic and attitudinal factors that modify annoyance from transportation noise, J. Acoust. Soc. Am. (1999) 105(6):3336-3344, 1999.

Milford I., Høsøien C.O., Løvstad A., Rindel J. H., Klæboe R., “Socio-acoustic survey of sound quality in Dwellings in Norway”, Proceedings Inter-noise 2016, Hamburg, Germany (2016).

Monteiro C., Machimbarrena M., De la Prida D., Rychtáriková M., Subjective and objective acoustic performance ranking of heavy and light weight walls. Applied Acoustics, Vol. 110, p268-279, 2016.

Morfey C.L., Dictionary of Acoustics, Academic Press, Trowbridge, UK, 2001.

Nagelkerke N. J. D., “A Note on a General Definition of the Coefficient of Determination”, Biometrika 78(3). 1991, 691-692.

Negreira J., Vibroacoustic performance of wooden buildings, Doctoral Thesis, Engineering Acoustics, LTH, Lund University, Lund, Sweden, 2016.

Park H. K., Bradley J. S., Evaluating standard airborne sound insulation measures in terms of annoyance, loudness and audibility ratings. J. Acoust. Soc. Am., Vol. 126(1):208-219, 2009.

Park H. K., Bradley J. S., Gover B. N., Evaluating airborne sound insulation in terms of speech intelligibility. J. Acoust. Soc. Am., Vol. 123(3):1458-1471, 2008.

Park S.H., Lee P.J., Reaction to floor impact noise in multi-storey residential buildings: The effects of non-acoustic factors, J. Applied Acoustics (2019) 150:268-278, 2019.

Pedersen T. H., Antunes S., Rasmussen B., Online listening Tests on Sound Insulation of Walls – A Feasibility Study, Proceedings Euronoise Prague 2012, Czech Republic, 2012.

R. Öqvist, F. Ljunggren, R. Johnsson, Listening test of walking noise from 20 Hz in dwellings, Proceedings Inter-noise 2017, 3935-3942, Hong Kong, China, 2017.

Rasmussen B., Rindel J. H., Concepts for evaluation of sound insulation of dwellings – from chaos to consensus? , Proceedings Forum Acusticum 2005 Budapest, Hungary (2005).

Rasmussen B., Sound insulation between dwellings - Requirements in building regulations in Europe, J. Applied Acoustics 71, 373-385 (2010).

Rasmussen B., Rindel J. H., Sound insulation of dwellings – Legal requirements in Europe and subjective evaluation of acoustical comfort, Proceedings DAGA'03 Aachen, Germany (2003).

Rawlings J.O., Pantula S.G., Dickey D.A., Applied Regression Analysis - A Research Tool, Springer, 2nd Edition, 1998.

Rice J.A., Mathematical Statistics and Data Analysis, International Edition, Brooks/Cole Cengage Learning, 2007.

Rindel J. H., Acoustic Quality and Sound Insulation Between Dwellings, J. Building Acoustics 5, 291-301, (1999).

Rindel J. H., Rasmussen B., Assessment of airborne and impact noise from neighbors, Proceedings Inter-noise 97, 1739-1744, Budapest, Hungary (1997).

Rindel J.H., Acoustical Comfort as a Design Criterion for Dwelling in the Future, Proceedings Sound in the Built Environment, Auckland, Keynote lecture (2002).

Robin X., Turck N., Hainard A., Tiberti N., Lisacek F., Sanchez J.-C., Müller M., pROC: an open-source package for R and S+ to analyze and compare ROC curves, BMC Bioinformatics 7:77, 2011.

Russel J. A., A circumplex model of affect, J. Personality and Social Psychology 39(6):1161-1178,1980.

Rychtáriková M, Müllner H, Urbán D., Chmelík V, Roozen N. B., Glorieux C., Influence of Temporal and Spectral Features of Neighbour's noise on perception of its Loudness, Proceedings Euronoise Innsbruck 2013, Austria, 2012.

Rychtáriková M, Roozen B, Müllner H, Stani M, Chmelík V, Glorieux C., Listening test experiments for comparisons of sound transmitted through light weight and heavy weight walls. Akustika – Vol.19:1-10, Czech Republic, 2013.

Rychtáriková M., Muellner H., Chmelík V., Roozen N. B., Urbán D., Garcia, D. P., Glorieux C., Perceived Loudness of Neighbour Sounds Heard Through Heavy and Light-Weight Walls with Equal R_w+ C_(50-5000), Acta Acustica united with Acoustica, Vol. 102(1):58-66, 2016.

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.;129(5):3047-55, May, 2011.

Schreckenberg D., Griefahn B., Meis M., The associations between noise sensitivity, reported physical health and mental health, perceived environmental quality and noise annoyance, J. Noise & Health (2010) 12(46):7-16, 2010.

Schünemann H., Hill S., Guyatt G., Akl E. A., Ahmed F., The GRADE approach and Bradford Hill's criteria for causation, J. Epidemiol. Community Health 65, 392-5 2011.

Sheskin D.J., Handbook of Parametric and Nonparametric Statistical Procedures, 2nd Edition, CRC Press, 2000.

Sheskin D.J., Handbook of Parametric and Nonparametric Statistical Procedures, 2nd Edition, CRC Press, 2000.

Simmons C., Hagberg K., Backman E., “Acoustical Performance of Apartment Buildings – Resident's Survey and Field Measurements”, AkuLite Report 2(2011), SP Report 58, 2011.

Simmons C., Ljunggren F., “Aku20 – Searching for optimal single number quantities in EN ISO 717-2 correlating field measurements 20-5000Hz to occupant’s ratings of impact sounds – New findings for concrete floors", EuroNoise 2015, Maastricht, Netherlands, 2015.

SIS SS 25267, Acoustics- Sound classification of spaces in buildings – Dwellings (in Swedish), Swedish Standards Institute, Stockholm, Sweden, 2015.

Späh, M., Hagberg, K., Bartlomé, O., Weber, L., Leistner, P., Liebl, A., Subjective and Objective Evaluation of Impact Noise Sources in Wooden Buildings, Building Acoustics, Vol.20(3), p193-214. September, 2013.

Tachibana H., Hamado Y., Sato F., “Loudness evaluation of sounds transmitted through walls—Basic experiments with artificial sounds,” J. Sound Vib., Vol.127(3):499-506, 1988.

Tavakol M., Dennick R., Making sense of Cronbach’s alpha, International Journal of Medical Education 2011;2:53-55, 2011.

Truax B., Handbook for Acoustic Ecology, No. 5, Music of the Environment Series, World Soundscape Project, A.R.C. Publications, 1978.

Västfjäll D., Friman M., Gärling T., Kleiner M., The measurement of core affects: A Swedish self-report measure derived from the affective circumplex. Göteborg Psychological Reports, 2000(30), No.8, 2000.

Vian J.-P., Danner W. F., Bauer J. W., “Assessment of significant acoustical parameters for rating sound insulation of party walls,” J. Acoust. Soc. Am. Vol.73(4):1236-1243, 1983.

Vidal R., Ma Y., Sastry S.S., Generalized Principal Component Analysis, Springer, 2003.

Vigran. T.E., Building Acoustics. Taylor & Francis Group, 2008.

Virjonen P., Hongisto V., Oliva D., Optimized single-number quantity for rating the airborne sound insulation of constructions: Living sounds, J. Acoust. Soc. Am., Vol. 140(6):4428-4436, 2016.

Weinstein N.D., Individual differences in critical tendencies and noise annoyance. J. Sound and Vibration (1980) 68:241-8, 1980.

Yeon J.Y., Jeong J.H., Objective and subjective evaluation of floor impact noise, J. Temporal Design in Architecture and the Environment, Vol.2(1) (2002), 20-28, 2002.

Yeon J.Y., Subjective evaluation of floor impact noise based on the model of ACF/IACF, J. Sound Vib., Vol.241(1)(2001), 147-155, 2001.

Part II

Research publications and attachments

Paper A

Soundscapes of buildings and built environments

BUILDING ACOUSTICS

Building Acoustics
1–20

DOI: 10.1177/1351010X18762687
journals.sagepub.com/home/bua
SAGE

Review of acoustic comfort evaluation in dwellings—part I: Associations of acoustic field data to subjective responses from building surveys

Nikolaos-Georgios Vardaxis[1], Delphine Bard[1] and Kerstin Persson Waye[2]

Abstract

Acoustic comfort is a concept hardly described in the literature. But it has been used in engineering typically to refer to low noise or annoyance in order to invoke no discomfort. Current standardized methods for airborne and impact sound reduction are deployed to assess acoustic comfort in dwellings. However, the measured sound pressure levels do not represent comfort. The latter should include further the human perception of the acoustic environment. Therefore, this article reviews studies that approached acoustic comfort through the association of objective and subjective field data, combining in situ acoustic measurements and survey responses from residents. We evaluated the studies using Bradford Hill's criteria. Most researches focus on self-reported noise annoyance while some others on satisfaction responses. Many studies were found incomprehensibly described: often vital data of statistical evaluation or study design are lacking. The results indicate that noise is a significant issue in living environments, especially certain impact noise types. The use of extended low-frequency spectra down to 50 Hz was suggested for impact measurements in order to predict better self-reported noise response. Greater problems with low-frequency transmission are displayed in lightweight structures which perform inefficiently compared to heavyweight components. Harmonization of presented results and study design details should be taken into account for future articles.

Keywords

Acoustic comfort, field measurements, subjective responses, association, indicators

[1]Division of Technical Acoustics, Department of Construction Sciences, LTH, Lund University, Lund, Sweden
[2]Department of Occupational and Environmental Medicine, University of Gothenburg, Goteborg, Sweden

Corresponding author:
Nikolaos-Georgios Vardaxis, Division of Technical Acoustics, Department of Construction Sciences, LTH, Lund University, V-huset, våning 5, John Ericssons väg 1, 221 00 Lund, Sweden.
Email: nikolas.vardaxis@construction.lth.se

Introduction

This article concerns a review of acoustic comfort evaluation during field studies in residencies, which include acoustic measurements of building structures and surveys or interviews with residents in their actual living environment. The scope of this review is to collect and examine those studies which combine acoustic data and subjective responses in order to approach acoustic comfort.

Despite being an important concept in engineering, acoustic comfort is vaguely defined and explored in the literature. So far, the term has been used in a general sense by engineers and designers, usually to refer to conditions with little noise and disturbances in a certain space. However, most publications do not offer a concept description, even when they use the term "acoustic comfort" or quality in their title.[1]

A first definition in the literature is provided by Rindel[2] and then repeated in some following articles.[3–5] The description offered for acoustic comfort is "a concept that can be characterized by absence of unwanted sound and opportunities for acoustic activities without annoying other people." This definition offers a user's perspective rather than a relation to merely acoustic measured data: acoustic comfort, for a certain person, is a combination of the person as a receiver of sound as well as a source. This means that a person can be disturbed by his or her own sounds because the sounds are truly disturbing or just because others might be disturbed, and dissatisfaction or conflicts might arise.

Past research has shown that measurements and metrics that acousticians use in order to assess building acoustic conditions may not always be representative of how residents perceive acoustics in their living environment. For example, tenants might have problems with impact noise types or vibration transmission from neighboring flats in the low-frequency range that is partially omitted from measurement spectra.[6]

Developments in the construction industry, such as the use of wood as a building material, create a demand for higher standards to be met in dwellings. Various regulations exist in several countries to assess sound insulation issues from noise inside or outside a building.[5] Residents still report complaints about noise from neighbors, outside road traffic, indoor technical installations, or other sources.[6–15] A central concern is thus how well the perception of residents corresponds to the results acquired by acoustic measurements and the descriptors of sound insulation in buildings. The latter are defined in a list of related standards, and variations of these are sometimes proposed in order to achieve better levels of agreement. Statistical methods have been used to examine how well building acoustic descriptors correlate to the subjective ratings of tenants, in field or laboratory studies. If they do, it is possible to formulate models for prediction of satisfaction and comfort for the building users.

For all the above reasons, sound perception and noise annoyance issues remain popular. However, the available research results usually come from small studies and remain insufficient (small samples) suggesting a demand for further research. Consequently, the idea of associating and comparing data of human sound perception to technical acoustic data seems essential. This article provides a systematic review in the association of subjective responses and acoustic data, in field studies in buildings. The overall purpose for examining this association is to evaluate, simulate, and maybe predict the response of residents and approach the concept of acoustic comfort.

Methods

The following databases were used to search for peer-reviewed publications and conference proceedings, offering investigation or comparisons between acoustic field data and subjective responses relevant to building acoustic studies: ScienceDirect, AIP Scitation, Ingenta Connect, ResearchGate, PubMed, Scopus, and Google Scholar. Several keywords in different orders and combinations were used, such as objective, subjective, acoustic, psychoacoustic, self-report, rating, score, comfort, quality, airborne, impact, sound, insulation, noise, annoyance, assessment, association, correlation, evaluation, comparison, building, and dwellings. Many times, the searches did not return a useful outcome for the scope of this review. Then, some studies were found in the references of the relevant publications, which were found initially.

Review criteria

Requirements for inclusion of articles in this review were the comparison of results between field acoustic data and subjective responses in the actual living environments as well as the use of statistical methods for the association of those data. The subjective data are obtained from residents with questionnaire surveys or interviews. In the end, 50 articles were found during the search in databases or relevant references; 24 of them were decided to be included in this review,[1–24] which correspond to 10 complete studies. The excluded studies[25–51] concerned mostly laboratory studies and not field studies.

The exclusion criteria, besides article context, were the year of publication and language. A threshold was set to 1985, because the earlier research studies found were few and very limited in results. Also, few of them were national publications, written not in English but in German, for example, so we could not translate and analyze them properly. The review search took place from April 2015 until September 2017.

Summary of methods, metrics, and quantities in the reviewed studies

Many different indicators (or descriptors) have been used to represent different quantities in acoustic measurements. They are all standardized in international ISO or other national standards, which usually comply with ISO. Many variations of them exist as well, since experimental research has been done to acquire better indicators than the standardized ones. A tabulation of all indicators presented in this review as well as the standards in which they are defined is presented in Table 1.

For the calculation of indicators such as R'_w or $L'_{nT,w}$, after the actual airborne or impact sound measurements, a predefined reference curve in the 1/3 octave spectra is used for comparison. The latter curve is shifted higher or lower with steps of 1 dB until the sum of deviations (between the measured and the reference curve) is maximum without exceeding 32 dB. Then, the value of the shifted reference contour at 500 Hz is used as the single number indicator of the measured building component, wall or floor.[57–60] Detailed analysis and review of the descriptors for airborne and impact sound insulation can be found in the existing literature, with a complete study of European indicators and comparison with suggested values in national regulations presented by Rasmussen and Rindel.[5] Note that the sound transmission class index STC used in the US standards is actually a reduction index which is calculated similar to the airborne sound reduction index R_w.

Several statistical methods are used in the studies, by means of statistical correlations and regression analyses, which associate acoustic data and subjective responses. The quality of statistical association is described with typical parameters:

The correlation coefficient, denoted as r, ρ, or R, is a measure of the strength and the direction (slope) or the linear relationship between two variables, taking values $0 < |r| < 1$. If r is positive, the linear relation is positive and upward, that is, the higher value for the independent variable X means the higher value for the dependent variable Y. If r is negative, the opposite occurs, that is, higher X

Table 1. Descriptions of the acoustic indicators used in the reviewed studies.

Indicator	Description	Standards	References
R'_w	Apparent airborne sound reduction index (same as R_w, for field measurements)	ISO 717-1, ISO 140-4, EN ISO 12354-1, ISO 16283-1	6–13, 24, 52–55
STC	Airborne sound transmission class, calculated similar to R_w	ASTM E413	16–19
$D_{nT,w}$	Apparent standardized level difference index	EN ISO 12354-1	14, 52, 53
$L'_{n,w}$	Weighted standardized impact sound pressure level	ISO 717-2, ISO 140-7, EN ISO 12354-2, ISO 16283-2	6–18, 20–24, 52–55
C	C is an A-weighted pink noise spectrum adaptation term	ISO 717-1, -2, EN ISO 12354-1, -2	6–12
$C_{50-3150}$	C adaptation terms, frequency range 50–3150 Hz	Same as C	6, 14, 24
$C_{I,20-2500}$	C adaptation terms, frequency range 20–2500 Hz	Same as C	6–12
$C_{I,AkuLite,20-2500}$	C adaptation terms, frequency range 20–2500 Hz	Same as C	6–12
L_{AFmax}	The Japanese rubber ball impactor index	JIS A 1418-2	6, 13, 56

means a lower dependent response Y. A coefficient of value 1 describes a perfect positive linear relationship between the data.

The coefficient of determination, denoted as R^2, is the squared correlation coefficient in the case of simple regression with one dependent variable. It is a measure of how well the regression line model represents the data. It is defined as the ratio of the explained variation to the total variation, so it indicates the percentage of variables positioned closest to the fitting line in terms of statistical significance. Both coefficients take values between zero and one $(0 \leq |r| \leq 1)$ and can be also expressed as a percentage, for example, $r = 85\%$ instead of 0.85. In this review, the correlation as percentage is preferred, to avoid confusions between the positive or negative slopes in different cases of airborne or impact sound insulation which differ.

The p-value and the confidence intervals (CIs) are measures of statistical significance, meaning the probability for the real result (which we approach with statistical methods) to be different than the observed, that is, the outcome of the statistics.

Evaluation of included studies

The quality of evidence for studies in this review was evaluated using Bradford Hill's criteria,[61] which is an evidence classification method often used in epidemiology and health studies. The fulfilled criteria are rated in a scale of high (+++), moderate (++), and low (+). The results are tabulated in Table 2, while the criteria used for evaluation are as follows:

Strength of association: it refers to the causality proven by the association between the studied variables (cause, effect size, and confounding factors).

Consistency: indicates the degree of certainty when similar results are observed by different studies in different tests.

Specificity: specific factors and effects on a specific population lead to a more likely causal relationship.

Table 2. Evaluation of the presented studies according to selected criteria.

References	Publication type	Strength of association	Consistency	Specificity	Temporality	Biological gradient	Plausibility	Coherence	Experiment design	Analogy
1	++	++	+	+	+	++	+	+	+	+
6	+++	+++	+++	++	++	++	++	++	++	++
7	++	++	++	++	++	++	++	++	++	++
8	++	++	++	++	++	++	++	++	++	++
9	++	++	++	++	++	++	++	++	++	++
10	+	++	++	++	++	++	++	++	++	++
11	+++	++	++	++	++	++	++	++	++	++
12	++	++	++	++	++	++	++	++	++	++
13	++	+	+	+	+	+	+	+	+	+
14	+++	+++	++	++	++	++	++	++	++	++
15	++	++	++	++	++	++	++	++	++	++
16	+++	+++	++	++	++	++	++	++	++	++
17	++	+++	+++	++	++	+++	+++	+++	++	++
18	+++	+++	+++	++	++	+++	+++	+++	++	++
20	+	++	++	+	+	++	++	++	+	+
21	++	++	++	+	+	++	++	++	+	+
22	+++	+++	+++	++	++	+++	+++	+++	+++	++
23	+	+++	++	++	++	+++	+++	+++	+++	++
24	+++	++	++	++	++	+++	++	++	++	++

+++: scientific journal; ++: conference article; +: report.
The references are grouped according to the research study they present: [1,6–10,11–12,13,14,15,20,21–23,24,25,26,27,28].

Temporality: it is based on temporal relations between effects and used as an indicator for causality, meaning one effect occurring after an exposure.

Biological gradient: it refers to the relation between exposure and effect; usually bigger exposure leads to greater effect, but not always, while the opposite outcome can occur as well.

Plausibility: it means that a biological explanation of why a cause leads to a certain effect supports a reasonable causality.

Coherence: it is a condition meaning that a stated causal relationship should not contradict with other accepted results or knowledge.

Experiment: it refers to the study design parameters that guarantee a reasonable causation, such as randomization.

Analogy: the possibility of having or predicting analogous effects from similar factors without total evidence.

Publication type: an additional criterion that we added in order to rank the reviewed studies. Scientific journal articles are thoroughly peer reviewed, while conference articles are usually less well reviewed. There are also study reports from research organizations that may be scientifically conducted but not reviewed. Thus, publications were evaluated as follows: scientific journal, +++; conference article, ++; and technical report, +.

The evaluation of the included studies was conducted by the authors. The presented data were chosen according to their relation and importance for this review's context. In Table 3, an overview is presented for all the selected studies, which are tabulated with important details on study design, variables, and summary of results. The studies are analyzed in the next section. In Table 2, the evidence evaluation rating of the studies is presented according to Bradford Hill's criteria,[61] which were chosen because they focus on causation between exposure and effects. Other evaluation such as the GRADE approach[62] was not preferred as it focuses a lot on the study design; in building acoustics, most studies are cross-sectional or experimental, so they would be rated very low in such a case. Readers who would like to have a deeper insight in any specific study results, and conclusions may read the original publications using the references.

Reviewed results

The first extensive research took place in Europe in 1985, and it is reported by Bodlund.[16] It concerns the evaluation of the sound conditions in Swedish buildings, specifically for impact sound insulation. That study proposed a basic method set for further research in building acoustics, using objective and subjective assessment of noise, and it was cited in many following publications. A wide sample of 350 Swedish dwellings was used, and acoustic measurements of impact sound transmission took place in building blocks of houses. The residents were interviewed in order to provide their ratings on acoustic behavior of their home using a satisfaction scale ranging from 1 (quite unsatisfactory) to 7 (quite satisfactory). About 464 scores were collected from 398 participants. The constructions tested were 22 floors, concrete, or timber joist floors in a sample of both attached houses and multistory residencies. All the data were grouped and averaged according to the actual urban building blocks, which consisted of similar constructions. There were at least 6 different floor measurements and about 20 interviews per block.

The average impact sound index I_i (as defined in the old ISO Recommendation 717-2:1982) of the block's measurements was compared with the average rating score of the block's tenants, using linear regression analysis. For the mean impact sound index within a block, the typical standard deviation (SD) was reported at 3.7 dB. The study found that a mean rating of 4.4 of reported satisfaction corresponds to a 51% of the building tenants who regard their home acoustic conditions as good or very good. Thus, a lower response than that is considered not satisfactory for building standards in this article. The linear regression analysis of the data acquired a model of average $I_i = 86.3 - 5.4S$, where S stands for the subjective mean score with r = 73%; this gives a determination coefficient of R^2 = 0.53. Bodlund compared his results also using the other ISO-weighted indices, $\overline{L'_{n,w}}$ and A-weighted levels $\overline{L'_{n,A}}$ which is used nowadays and then he acquired different values for correlation r of 75% (R^2 = 0.56) and 72% (R^2 = 0.52), respectively.

Bodlund mentions that the tapping machine spectrum is different than the one excited by a person running; the tapping machine gives significantly higher amplitudes in middle and high frequencies, while walking excites mostly low frequencies on the floor structures. Furthermore, this effect is more intense in wooden structures, an argument which is supported in other following studies.[6]

Finally, Bodlund suggested that a new reference curve for the ISO 717 corrections with an emphasis on the low and middle frequencies would correlate better to subjective ratings. He used the study's results to calculate a new curve, that being a straight line from 50 Hz to 1 kHz with a slope of 1 dB/octave. In this case, the regression model for the average suggested index was $I_s = 86.3 - 5.53S$ and offered the best regression of 87%, with r = 0.87 (R^2 = 0.76). The

Table 3. Overview of the selected studies.

References	Sample and experiment details	Variables as defined in the study	Models and results	Parameters for evaluation	Summary of results
1	Synthesis of results from building surveys and measurements from other complete studies[18,19,61]	p: poor evaluation G: good evaluation F: fair evaluation by the residents	Exposure–effect curves and models not stated. Suggested relation: $P+F+G=100\%$	No details provided	Dose–response curves have an average slope of 4% in all studied cases
6–10	251 respondents to survey 10 Swedish multistory buildings for field measurements 2 HW structure 8 LW constructions Results in acoustic measurements and subjective responses were averaged per test building	Independent: $R'_w + C_{50-3150}$: weighted normalized airborne reduction $L'_{nT,w}$: weighted standardized impact sound Dependent: V1: mean annoyance toward airborne sounds from neighbors V2: mean annoyance toward impact sounds from neighbors above in a 11-point scale	Linear regression: R'_w to V1 $R'_w + C_{50-3150}$ to V1 $L'_{nT,w}$ $L'_{nT,w} + C_{50-3150}$ $L'_{nT,w} + C_{I,AkuLite,20-2500}$	Coefficients: $r=76\%, R^2=0.58$ $r=85\%, R^2=0.73$ $r=51\%, R^2=0.26$ $r=57\%, R^2=0.32$ $r=92\%, R^2=0.85$	Low-frequency spectra down to 20 Hz are essential for impact sound measurements and correlation to annoyance. Annoyance predicted well with descriptor $R'_w + C_{50-3150}$, not well with $L'_{n,w}$ but sufficiently with suggested descriptor: $L'_{n,w} + C_{I,20-2500}$
11, 12	Continuation of previous study[6–10] 800 extra respondents to survey 13 Swedish multistory buildings for field measurements, so 23 in total 6 HW 6 cross-laminated timber 11 LW constructions Results in acoustic measurements and subjective responses were averaged per test building	Independent: $L'_{nT,w}$: weighted standardized impact sound pressure level Dependent: V2: mean annoyance toward impact sounds from neighbors above in a 11-point scale	Linear regression: $L'_{nT,w}$ $L'_{nT,w} + C_{50-2500}$ $L'_{nT,w} + C_{20-2500}$ $L'_{nT,w} + C_{I,AkuLite,20-2500}$	Coefficients: $r=42\%, R^2=0.18$ $r=70\%, R^2=0.49$ $r=84\%, R^2=0.71$ $r=80\%, R^2=0.65$	Results from previous study confirmed, inclusion down to 20 Hz is essential for impact sound measurement to correlate well with self-reported annoyance. The low-frequency inclusion does not affect much the results from HW constructions in contrast to the LW ones

(Continued)

Table 3. (Continued)

References	Sample and experiment details	Variables as defined in the study	Models and results	Parameters for evaluation	Summary of results
13	Unknown number of respondents to survey 10 French multistory or detached buildings	Independent: $L'_{nT,w}$: weighted standardized impact sound pressure level Dependent: V2: mean annoyance to impact sounds from neighbors above in a 11-point scale	Linear regression: $L'_{nT,w} + C_{I,50-2500}$ to V2 L_{AFmax} to V2 $L'_{nT,w}$ $L'_{nT,w} + C_I$	Coefficients: $r = 89\%, R^2 = 0.79$ $r = 85\%, R^2 = 0.73$ $r = 86\%, R^2 = 0.74$ $r = 85\%, R^2 = 0.73$	$L'_{nT,w} + C_{I,50-2500}$ correlated best to ratings. Suggestions: $L'_{nT,w} + C_{I,50-2500} = 52$ dB and $L_{AFmax} = 54$ dB(A)
14, 15	600 Norwegian dwellings Nearly 720 respondents: 83% in concrete slab constructions and 17% in LW constructions	Independent: $L'_{n,w}$, $L'_{nT,w}$: weighted normalized and standardized impact sound pressure level Dependent: V1: annoyance to airborne sounds from neighbors V2: annoyance to impact sounds from neighbors above in a 5-order scale	Exposure–effect curves used but regression models not stated $D_{nT,w}$ offers best correlation with V1 $L'_{n,w} + C_{i,50-2500}$ correlates very well with V2 $L'_{nT,w} + C_{I,50-2500}$ correlates best with V2	Curves within 95% CI in all cases	Noise is a big issue for residents, especially low-frequency problems. $L'_{n,w}$ and $L'_{nT,w}$ do not correlate with V2 without correction terms
16	398 participants (350 flats) in Sweden 22 floors, concrete, or timber joist were measured. Results in acoustic measurements and subjective responses were averaged per building block in the study	Independent: I_i: old-type impact sound index $L'_{n,w}$, $L'_{n,A}$: weighted and A-weighted normalized impact sound pressure level Dependent: S: mean satisfaction response of tenants in a building block from 1 (quite unsatisfactory) to 7 (quite satisfactory)	Linear regression: $\overline{I} = 86.3 - 5.48S$ $\overline{L'}_{n,w} = 80.6 - 5.48S$ $\overline{L'}_{n,A} = 85.2 - 5.09S$ Suggested: $\overline{I}_S = 86.3 - 5.53S$ $S = 4.4$ corresponds to 51% of the resident sample	Coefficients: $r = 73\%, R^2 = 0.53$ $r = 75\%, R^2 = 0.56$ $r = 72\%, R^2 = 0.52$ $r = 87\%, R^2 = 0.76$	Good association exists between impact noise and subjective response. Low frequencies from 50 Hz should be considered in the measurement spectra. New reference curve suggested for ISO standard method correction to have better correlation levels

Table 3. (Continued)

References	Sample and experiment details	Variables as defined in the study	Models and results	Parameters for evaluation	Summary of results
17, 18	600 participants interviewed, 300 party walls measured in Canada. Results in acoustic measurements and subjective responses were clustered in 8 groups according to STC values	Independent: STC: weighted airborne sound reduction index, similar to R'_w Dependent: V1: want to move out? V2: satisfaction with building V3: considerate neighbors V4: neighbors' noise either side V5: neighbors' voices V6: neighbors' TV sound V7: neighbors' music V8: awakening from neighbors' noise V9: sound insulation satisfaction	Linear regression of STC with: V1: yes to move out V2: satisfaction for house V3: neighbors consideration V4: neighbors' noise general V5: neighbors' voice sounds V6: neighbors' TV sound V7: neighbors' music V8: sleep awakening V9: sound insulation rating (linear and Boltzmann equation models not stated)	Coefficients: $R^2 = 0.56, p = 0.033$ $R^2 = 0.83, p = 0.002$ $R^2 = 0.86, p = 0.001$ $R^2 = 0.82, p < 0.002$ $R^2 = 0.94, p < 0.001$ $R^2 = 0.77, p < 0.004$ $R^2 = 0.92, p < 0.001$ $R^2 = 0.60, p = 0.024$ $R^2 = 0.60, p = 0.024$	Suggested value STC = 60 dB would solve most annoyance problems. If STC = 50 dB, then annoyance from most noise types decreases significantly; above that level, there is some important. protection from music sounds. If STC = 55 dB, then circa 10% of the subjects are disturbed by general noise from neighbors
20, 21	Synthesis of results from building surveys and measurements from the original and another study[6]	Independent: I_i: old impact sound index[6] $L'_{nT,w}$: weighted standardized impact sound pressure level Dependent: S: mean satisfaction response of tenants in a building block T: percentage of satisfied tenants	Linear regression: $L'_{nT,w} = 80.6 - 5.48\underline{S}$ $L'_{nT,w} + C_{I,50-2500} = \overline{T} - 6.4$ Suggested combination of equations: $L'_{nT,w} + C_{I,50-2500} = -0.25 + 68.3$	Coefficients: $r = 75\%, R^2 = 0.56$ $r = 96\%, R^2 = 0.92$	Low frequencies below 100 Hz are important for accurate measurements. Unsatisfactory self-reports if $L'_{n,w} < 48$ dB. Minimum 53 dB suggested for $L'_{nT,w}$ and $L'_{nT,w} + C_{I,50-2500}$

(Continued)

Table 3. (Continued)

References	Sample and experiment details	Variables as defined in the study	Models and results	Parameters for evaluation	Summary of results
22, 23	198 participants in Sweden 22 floors of several structure types were measured; 12 building data taken from Bodlund.[16] Results in acoustic measurements and subjective responses were averaged per building block in the study as in Bodlund[16]	Independent: $L'_{n,w,new,i}$: weighted impact sound index combined with suggested new reference curves Dependent: S : mean satisfaction response of tenants in a building block from 1 (quite unsatisfactory) to 7 (quite satisfactory)	Linear regression: $\overline{L'}_{n,w,new,01} = 76.29 - 4.10S$ $\overline{L'}_{n,w,new,02} = 77.69 - 4.12S$ $\overline{L'}_{n,w,new,03} = 79.28 - 4.09S$ $\overline{L'}_{n,w} = 75.35 - 4.58S$ $\overline{L'}_{n,w} + C_I = 73.31 - 4.22S$ $\overline{L'}_{n,w} + C_{I,50-2500} = 74.4 - 4.17S$	Coefficients: $r = 85\%, R^2 = 0.73$ $r = 86\%, R^2 = 0.74$ $r = 87\%, R^2 = 0.76$ $r = 74\%, R^2 = 0.55$ $r = 79\%, R^2 = 0.62$ $r = 84\%, R^2 = 0.71$	Good association between impact noise and subjective response. New reference curve suggested for ISO standard method correction to achieve better correlation with subjective ratings. Low frequencies from 50 Hz need to be considered in the measurement spectra
24	159 residents in Finland 4 HW buildings, 2 LW buildings were included in a survey to compare responses from various structures	Independent: R'_w and $R'_w + C_{50-3150}$ were equal for different structure types HW, LW Dependent: Several variables	Mann–Whitney *U*-test	Values within 95% CI in all cases	No significant differences found based on the responses of residents from different building types

HW: heavyweight; LW: lightweight; CI: confidence interval.

suggestions for reference curves are part of a trend for ISO method corrections in the past literature, but it is not further described in this article.

In the same time with the previous studies, a similar study took place in Canada by Bradley[17,18] for investigation of airborne sound insulation in a wide sample of 300 constructions, row housing and multifloor buildings, in three cities. Acoustic measurements were performed in the party walls between houses, and interviews were taken face to face with 600 tenants. Responses to questions were given using a 7-point scale. The association of airborne sound reduction index and personal responses was analyzed by fitting linear regression models or sigmoidal Boltzmann equations. However, the models are not stated but only their R^2 and p-values, while the results with the fitting models are presented in graphs. The measured apparent STC values had a range of 38–60 dB (mean: 49.8 dB) as measured according to ASTM.[16]

When the residents were asked if they want to move out of their home due to noise, more than 94% replied positive, indicating that neighbor noise is a serious issue (fitted line slopes down with increasing STC reduction, $R^2 = 0.56, p = 0.033$). The STC values were found to be significantly related to the residents' satisfaction for their buildings ($R^2 = 0.83, p = 0.002$), as well as the feeling of having neighbors who consider to avoid making noise ($R^2 = 0.86, p = 0.001$). Specifically, STC values were associated with dissatisfaction from neighbors' general noise from either side of the wall ($R^2 = 0.82, p < 0.002$), neighbors voice sounds ($R^2 = 0.94, p < 0.001$), neighbors' TV sounds ($R^2 = 0.77, p < 0.004$), and also neighbors' music ($R^2 = 0.92, p < 0.001$). It is stressed that annoyance depends not only on airborne sound reduction but also on noisy behavior of neighbors and how often neighbors make noise. Then, the STC values were associated with sleep awakening due to neighbor's noise ($R^2 = 0.60, p = 0.024$) and the subjective rating of the tenants for the building's sound insulation ($R^2 = 0.92, p < 0.001$). It is concluded in the study that after a minimum value of 50 dB for STC, the annoyance coming from most noise types decreases importantly. Above STC = 50 dB, there is some protection from music sounds transmission as well. Based on their results, the authors suggest a value of STC = 60 dB as an optimal solution since very few people would be annoyed then.

In the previous studies,[1–2,20–22] the conclusions presented deal with a synthesis of results of previous studies in different countries which took place between the years 1972 and 1997. A short review of those studies is included in Hveem et al.[20] and Rindel and Rasmussen.[21] Sound insulation data from buildings and self-reported noise annoyance data were compared in order to assess the satisfaction perception of building tenants.

Some further analyzed results from Bodlund[16] are used in Hveem et al.[20] and Rindel and Rasmussen[21] where another regression model was developed which was finally expressed as $L'_{n,w} = 80.6 - 5.48S$ and offered a correlation of 75% (R^2 = 0.56). The study of Hagberg[23] is referred, which evaluated Bodlund's curve during impact sound measurements in 146 buildings using also the low-frequency spectrum adaptation terms $C_{I,50-2500}$. Another relation presented is $L'_{n,w} + C_{I,50-2500} = L_B - 6.4$, where L_B is the average impact sound index I_i from Bodlund,[16] and the acquired correlation between the two metrics is 96% ($R^2 = 0.92$). Finally, using the combination of the last equation and others from previous studies,[2,18,16] a new relation is derived, which can be used as a prediction model for subjective satisfaction of inside acoustic conditions: $L'_{n,w} + C_{I,50-2500} = -0.25T + 68.3$ with the same parameters r = 96% ($R^2 = 0.92$) that seems the most successful regression model developed in all selected studies.

In Hveem et al.,[20] another self-report assessment is published where 17 floor structures in multistory buildings were rated as satisfactory/good, barely satisfactory, or unsatisfactory. The observations indicated that the overall subjective response is satisfactory or good when the $L'_{n,w}$ value is 5–10 dB lower than the Nordic minimum requirement of 58 dB. Therefore, a minimum suggestion is made for both $L'_{n,w} \le 53\,\text{dB}$ and $L'_{n,w} + C_{I,50-2500} \le 53\,\text{dB}$. The authors highlight also the need to include the low-frequency range below 100 Hz in the impact sound assessment and stress that human-induced vibrations affect the overall acoustic sense of floor structures as well.

In the study of Rindel,[1] a subjective satisfaction model is suggested, after observations from the studies examined before,[20] which is $P+F+G=100\%$. The variables P, F, and G stand for subjective evaluation by the inhabitants as poor, fair, and good, respectively. It is also observed that the percentage for F typically approaches 30%. The linear regression slopes A from past studies are compared, in cases where the correlation coefficients are $|r| > 0.7$ to be considered as good correlations for the researchers. It is summarized that dose–response curves have an average slope of 4% per decibel in the examined cases, after comparing insulation levels and subjective annoyance. The latter means that for every additional decibel in the noise pressure levels, airborne or impact, the satisfaction of the tenants decreases 4%, in the satisfaction scales. The satisfaction scales are not the same for every combined result from different studies, although those results are claimed to be valid for all cases of airborne and impact noise generated from co-habitants, as well as road traffic noise in dwellings. Besides dissimilar scales, shortcomings are also reported due to different definitions of subjective parameters (poor, fair, good, satisfaction, etc.) in different surveys (questionnaires and oral interviews). No specific information is reported on how to handle those discrepancies.

Additional conclusions by Rindel and Rasmussen[21] stress the need for low-frequency adaptation terms for improved correlation between airborne and impact sound insulation and subjective responses of tenants. This problem concerns mostly timber structures due to their poor performance in low frequencies down to 20 Hz. There is also an ad hoc suggestion mentioned for airborne sound insulation to be satisfactory, at least 2/3 of the tenants should consider it good which corresponds to a minimum of $R'_w = 60\,\text{dB}$.

In a following study by Hagberg,[22,23] the results from Bodlund[16] were enriched with new data, and they were reprocessed. Another 10 Swedish buildings of various structures were tested with impact sound measurements; 198 new participants were interviewed with the same method. The new data were combined with previous measurements from 12 buildings from a previous study[16] to make up a total sample of 22 buildings. Linear regression models were performed again to test the data association between residents' satisfaction and impact sound index values. All data were averaged again per building block as before in Bodlund.[16] New reference contours were tested too, as well as the previous suggested Bodlund's reference curve, which was found insufficient to associate well with the new sample data.

The apparent airborne sound reduction index $R'_w + C_{50-3150}$ was very well predicted by the user's ratings of perceived airborne noise transmission, having a correlation of 85% ($R^2 = 0.73$) but not so well when omitting the adaptation terms: without $C_{50-3150}$, it was 76% ($R^2 = 0.58$). Contrary to airborne sound, the standardized impact sound index $L'_{n,w}$ was poorly correlated to the relevant questions for impact noise annoyance r = 51% ($R^2 = 0.26$), even when using adaptation terms $L'_{n,w} + C_{50-3150}$ (r = 57%, $R^2 = 0.32$). One explanation for that is the lack of important low-frequency content in the measurements, which affects the final value of the descriptor $L'_{n,w}$. However, the suggested improved index $L'_{n,w} + C_{I,20-2500}$ which has a spectrum adaptation expanding down to 20 Hz was much better correlated r = 86% ($R^2 = 0.74$) indicating that impact sound assessment should include the very low-frequency content as well. Finally, another adaptation term curve is proposed within this project, the $C_{I,AkuLite,20-2500}$, which follows the same weights of ISO 717-2 between 50 and 400 Hz, increases 2 dB per 1/3 octave bands below that and increases 1 dB per 1/3 octave band after 400 Hz. The optimal results acquired in regression between occupants responses and $L'_{n,w} + C_{I,AkuLite,20-2500}$ had a correlation coefficient of r = 92% ($R^2 = 0.85$).

Previous studies[6–15] have many aspects in common; since they are contemporary, they follow the same methodology and occurred about the same period. First, they all deal with the subject of evaluation of acoustic comfort in multistory family dwellings, based on the combination of objective and subjective data. They use standardized procedures of airborne and impact sound (standardized tapping machine and Japanese rubber ball) following the relevant standards (ISO 717-1 and -2,[57,58] ISO 140-4 and -7,[59,60] EN 12354-1 and -2,[52,53] and JIS A 1418-2[56]), for the characterization of sound insulation of building elements. The acoustic measurements took place in selected living rooms or bedrooms in the study buildings in every case. Questionnaires were developed, for the rating of noise assessment into the participants' apartments based on a common methodology described in Simmons[63] and following ISO 15666.[64] In all cases, the question formulations included annoyance due to noise and vibration from neighboring apartments, noise from neighbors in common or collective spaces, noise from technical installations or equipment, outdoor noise, and noise inside the tenant's apartment. Then, the results between acoustic measurements and perceived noise annoyance were compared, and the degree of association among the collected data was investigated.

In previous articles,[6–10] the AkuLite research program is presented, a study with a sample of 10 Swedish multistory buildings: a typical heavy concrete building and 9 lightweight (LW) structures (4 wooden, 4 made of cross-laminated timber, and 1 of steel framework). A total of two typical rooms one above another were measured acoustically in each test building. A total of 251 responses were collected from participating tenants (reported response rate circa 30%) of the test buildings. The AkuLite questionnaire consisted of 15 questions concerning noise annoyance inside apartments. The measurement data and subjective responses, grouped in mean values for every building, were evaluated statistically using linear regression analysis within 95% CI.

The apparent airborne sound reduction index $R'_w + C_{50-3150}$ was very well predicted by the user's ratings of perceived airborne noise transmission, having a correlation of 85% ($R^2 = 0.73$) but not so well when omitting the adaptation terms: without $C_{50-3150}$, it was 76% ($R^2 = 0.58$). Contrary to airborne sound, the standardized impact sound index $L'_{n,w}$ was poorly correlated to the relevant questions for impact noise annoyance $r = 51\%$ ($R^2 = 0.26$), even when using adaptation terms $L'_{n,w} + C_{50-3150}$ ($r = 57\%$, $R^2 = 0.32$). One explanation for that is the lack of important low-frequency content in the measurements, which affects the final value of the descriptor $L'_{n,w}$. However, the suggested improved index $L'_{n,w} + C_{I,20-2500}$ which has a spectrum adaptation expanding down to 20 Hz was much better correlated $r = 86\%$ ($R^2 = 0.74$) indicating that impact sound assessment should include the very low-frequency content as well. Finally, another adaptation term curve is proposed within this project, the $C_{I,AkuLite,20-2500}$, which follows the same weights of ISO 717-2 between 50 and 400 Hz, increases 2 dB per 1/3 octave bands below that and increases 1 dB per 1/3 octave band after 400 Hz. The optimal results acquired in regression between occupants responses and $L'_{n,w} + C_{I,AkuLite,20-2500}$ had a correlation coefficient of $r = 92\%$ ($R^2 = 0.85$).

The results of the AkuLite project were enriched in a continuation study presented by Ljunggren et al.[11,12] Acoustic measurements and surveys in another 13 Swedish buildings took place, since the previous sample of buildings was limited according to the authors. The same methodology was followed, and about 800 responses were collected; the associations of standardized impact noise levels measured with tapping machine to self-report annoyance were explored from the total sample number of 23 buildings. Again, the standardized impact sound index $L'_{nT,w}$ was poorly correlated with subjective annoyance from footstep noise ($R^2 = 0.18$). Better results were acquired with the inclusion of lower frequencies from 50 Hz in the index calculations, offering a determination coefficient of $R^2 = 0.49$ for $L'_{n,w} + C_{I,50-2500}$. Even better results were acquired from 20 Hz, with values of $R^2 = 0.71$ for the standardized $L'_{n,w} + C_{I,20-2500}$ and with $R^2 = 0.65$ for the indicator $L'_{n,w} + C_{I,AkuLite,20-2500}$. The previous results from Ljunggren et al.[6] were confirmed. This study also included in the sample six heavyweight (HW) concrete buildings instead of only two as in the previous study. It was highlighted that for HW cases, inclusion of low frequencies does not change the results drastically as for the LW cases, which show an undesired acoustic behavior in the low-frequency range.

Summing up for the AkuLite project, the perception outcome of the tenants' responses indicates that the noise annoyance due to airborne sound transmission is generally low, and the correlation of objective and subjective data is sufficient. In contrast to that, low-frequency noise induced by impact sound was found to be the highest recorded source in both acoustic measurements and self-reported noise annoyance. The indicators $L'_{nT,w}$ and $L'_{n,w} + C_{I,50-2500}$ were found poorly associated with self-reported annoyance. To achieve a sufficient correlation between impact sound index and subjective assessment, the low-frequency range down to 20 Hz is considered essential. This study did not only confirm the importance of low-frequency range in the measurements but further claimed expansion down to 20 Hz, instead of 50 Hz as in Bodlund[16] and Hagberg.[22,23]

In Guigou-Carter et al.,[13] 10 various construction buildings were measured for the French study project Acoubois, some multistory ones and some attached houses. The survey included questions about annoyance from several noise types, similar to Ljunggren et al.[6] The sample size and response rate are not stated in the publication (reported only 57% females, age span 26–59 years), as well as other essential data about the study design. In the study results, 85% of the tenants reported sound insulation to be very important. Overall, more than 50% did not report any annoyance, which is considered as a satisfactory result for the French regulations according the authors.

The correlation coefficients were calculated for some questions corresponding to the measurements of airborne and impact sounds. According to that study, the best correlation found for the impact sound index $L'_{n,w} + C_{150-2500}$ to the self-reported impact noise annoyance with ($r = 0.89$, $R^2 = 79\%$). $L'_{n,w} + C_{150-2500}$ is assessed as better correlated than the Japanese ball impactor index L_{AFmax} ($r = 0.85$, $R^2 = 73\%$), $L'_{n,w}$ alone ($r = 0.86$, $R^2 = 74\%$), or $L'_{n,w} + C_I$ ($r = 0.85$, $R^2 = 73\%$). Some optimal values of $L'_{n,w} + C_{150-2500} = 52$ dB and $L_{AFmax} = 54\,\text{dB(A)}$ are suggested after the result evaluation. However, no statistical significant levels were presented for the results. The authors conclude that impact noises are more annoying than others for the tenants' comfort. More than 50% were from quite to very annoyed by impact noise from neighbors walking and 30% quite to very annoyed by vibrations from neighbors walking, moving, or dropping objects.

In the articles of Milford et al.[14] and Høsøien et al.,[15] another study is presented, which took place in Norway for the evaluation of subjective sound quality ratings in newly built dwellings (2002–2015). Field measurements in 600 buildings were done alongside a socio-acoustic survey with a questionnaire sent to the occupants of the buildings. In total, 702 residents answered to 35 questions, similar to the ones developed in JIS A 1418-2.[56] The articles elaborate on the responses from questions regarding annoyance due to airborne and impact sounds coming from neighbors from the above floor in a slightly differentiated scale from 1 (not annoyed) to 5 (extremely annoyed).

The results indicate that 65% of the occupants are at least slightly disturbed, and the authors emphasize on the wide problem of low-frequency noise; 33% report worried about their own TV, music, or speech annoying other occupants; 20% of the occupants report at least moderately annoyed by traffic noise or impact sounds from neighbors above. The articles mention that impact sound annoyance from neighbors above, especially footfall noise, is reported as stressing as road traffic annoyance. Bad correlation is reported between subjective ratings and the weighted impact sound indices $L'_{n,w}$ and $L'_{nT,w}$ unless the correction term $C_{I,50-2500}$ is included. $L'_{nT,w} + C_{I,50-2500}$ is thus reported as the best predictor of subjective annoyance within 95% CI. For airborne sounds annoyance, $D_{nT,w}$ is reported as the best descriptor to predict occupants' annoyance. Good agreement of the slopes of the dose–response curves with results from Rindel[1] is mentioned as well. Finally, it is reported that more than half of the residents questioned would be willing to pay an extra cost for better acoustic conditions.

Another building survey was setup in Finland[24] to compare acoustic satisfaction in different multistory building structures with similar airborne sound insulation of walls. Specifically, four

HW concrete buildings with measured $R'_w = 66\,\text{dB}$ (floors) and $R'_w = 56\,\text{dB}$ (walls) and two LW building structures with $R'_w = 63\,\text{dB}$ (floors) and $R'_w = 57\,\text{dB}$ (walls) were included. All buildings fulfilled the Finish Building Code requirements ($R'_w \geq 55\,\text{dB}$ and $L'_{n,w} \leq 53\,\text{dB}$). However, the sound insulation in low frequencies was significantly lower for the LW cases. A sample of 159 residents (72 in HW and 87 in LW) replied to a wide questionnaire, and they offered responses on noise annoyance to certain sources, satisfaction, noise sensitivity, and other variables. The associations between the variables were tested with nonparametric Mann–Whitney *U*-test, and results were reported within 95% CI. No significant statistical differences were found between the groups of residents, except for two control variables: education and extraversion, which were neglected. No significant differences were found for the examined building types (HW and LW) and dependent variables: willingness to move out (yes/no), distraction of performance, inconvenience from neighbor noises, and disturbance from certain noise sources. Loud speech, TV, and music were reported as the highest annoyance for airborne sound. Also, impact noise types such as footsteps, moving furniture, and closing doors were reported as the most disturbing. Inconvenience from outside noises, as well as disturbance to outside traffic noise, was higher for residents of LW buildings: that is reasonable concerning low acoustic performance at low frequencies for LW structures. However, technical installations noise was significantly higher in HW buildings.

Discussion

This review article concerns studies which include acoustic data from in situ measurements and self-reported responses from the residents, collected with surveys or interviews in test buildings. The selected field studies explore acoustic comfort in buildings through the association of objective and subjective data. Few researches were found to fulfill the aims of this review, namely, 10 separate studies reported in 24 articles. Noticeably eight of the analyzed field studies are Scandinavian, then one is French, and one is Canadian.

Most of the studies found during our search were conducted in laboratory tests, and subjective assessment was evaluated with listening experiments. The laboratory tests are easier to set up, but laboratory measurements ignore the interaction of the whole building structure during sound propagation. In contrast, field measurements capture the real acoustic behavior of structures. The mental state of a participant can be also different in a laboratory than being in the actual living environment and offering spontaneous judgments. Therefore, only results from field studies were chosen to be investigated in this review article.

From all the articles dealing with acoustic comfort and even including the term "comfort" or "quality" in their title, only two of them provide an actual definition of those concepts.[2,5] More definitions could be reported, and the writers should generally elaborate more on the concept of comfort.

The review revealed that noise issues in residential buildings are significant for acoustic comfort, especially impact noise sounds produced by neighbors that include many low-frequency components.[6–15] An overview of the noise types reported (and which ones were found most important) in the different studies is given in Table 4. Many studies report that specifically impact noise leads to high disturbance according to human perception results, mostly cases of impact sound from neighbors walking, either barefoot or not. Neighbors' steps from the above floor are reported as the most annoying noise source for residents.[6–13,16] Some study results are even more specific for noise types, such as in Ljunggren et al.[12] where footfall walking is stressed to be the biggest disturbance due to the excitation of many low frequencies that propagate through flanking transmission paths too, that is, through connected floors and walls.

Table 4. Noise types reported in the different case studies.

Noise types	References (one for each study)
Airborne noise in general from neighbors	14, 17
Airborne noise from neighbors in general (daily living, talking, audio, and TV)	6, 13, 14, 17, 24
Airborne noise from neighbors' music (low frequencies)	6, 14, 17
Impact noise in general from neighbors	6[a], 13, 14, 17[a]
Impact noise from neighbors moving/dropping objects	13, 14, 22, 24
Impact noise by footsteps (neighbors walking barefoot)	6, 13, 14[a], 16, 22, 24
Impact noise by neighbors walking on heels/hard sole shoes	6, 13, 14, 16, 22
Traffic noise	6, 13, 14, 24
Noise in common areas	13
Outdoor noise	13
Noise within a flat	13
Vibration induced from machinery in other flats	13
Vibration induced from neighbors' walking	13

[a]Reported as most annoying.

Many studies also conclude that extended frequency spectra which include frequencies below 100 Hz correlate better with self-reported responses on noise annoyance, especially for the impact sound cases.[1,6–14,16,17] This finding further underlines the observation that low frequencies could offer results for better prediction of human perception in living environments. Besides being an overall suggestion, it is considered a necessity for LW structures, where the most problematic noise propagation occurs in low frequencies, due to resonances of structural elements and coupling among them.[6] In LW building structures, the impact sound insulation standards can be met, and the $L'_{n,w}$ curve and the single value might look sufficient, but the residents might still complain firmly for low-frequency noise transmission. Further expansion of the whole frequency range down to 20 Hz has been recently suggested,[6–12] while ISO standards have 100 Hz as the lowest frequency limit; thus, researchers do not measure any lower frequencies. An exception there is in Sweden, where the national standards comply with ISO ones, but they demand measurements down to 50 Hz. In contrast to the results for impact sounds, the results for airborne sound insulation are not that ambiguous. Few complaints have been reported,[13] but generally occupants offer subjective ratings which indicate overall satisfaction.

Noise content with intense low-frequency characteristics can be more disturbing while propagating through LW building components. LW structures offer better sound reduction than HW ones but not in the low-frequency range.[6–10] Below around 100 Hz, the performance is expected to change, with poorer insulation of LW walls as indicated by the in situ studies.

In some articles, the authors suggest specific values for building acoustic indicators, which came up as efficient to represent a good level of acoustic conditions in every case study. The suggested values usually correspond to 50% satisfaction of residents, and they are presented in Table 5. The most important suggestions are as follows:

$R'_w \geq 60\,\text{dB}$, since it is suggested by Rindel and Rasmussen[21] and confirmed in a different study with the similar STC indicator by Bradley.[17]

$L'_{nT,w}$ and $L'_{n,w} + C_{I,50-2500} \leq 56\,\text{dB}$, coming from results of a complete wide study by Hagberg[22] published in a journal.

Table 5. Suggested acoustic indicator values corresponding to satisfaction.

Indicator	Minimum/maximum requirements	References	Publication type
STC	≥60 dB	17	++
R'_w	≥60 dB	19	++
R'_w	≥55 dB	14	++
$L'_{n,w}$ and $L'_{n,w}+C_{I,50-2500}$	≤48 dB	18	++
$L'_{n,w}$ and $L'_{n,w}+C_{I,50-2500}$	≤53 dB	18	++
$L'_{n,w}$ and $L'_{n,w}+C_{I,50-2500}$	≤56 dB	20	+++
$L'_{n,w}$	≤53 dB	12	++

+++: scientific journal; ++: conference article; +: report.

Concerning prediction models developed from the results, some of them are good with high determination coefficients, that is, high R^2 values, which explain the variance of the model. Best regression model from field measurements observed so far is $L'_{n,w}+C_{I,50-2500}=-0.25T+68.3$ ($r=0.96$, $R^2=92\%$), which came up as a synthesis of results from several articles.[16,20,21] The term T corresponds to the percentage of satisfied tenants.

Although statistical methods are used to compare and associate results from objective and subjective data, in the examined literature, many shortcomings take place in the study designs and reporting methods and results. First, the biggest problem observed in many studies is the lack or misuse of basic statistic indicators; some of them do not even mention the sample size of participants[13] or other parameters such as *p*-values. Furthermore, the presentation of the outcome is not always successful, even if it is important. In many studies, the regression models are presented with the independent variable (usually airborne or impact sound levels) on the *y*-axis and the dependent on the *x*-axis, while the opposite is the usual way for statistical data representation. In few cases, the regression models and parameters represent the opposite relationship between dependent and independent variables.[16,22] That makes the comparison or regression models and their parameters cumbersome. For most studies, there is no assumptions analyzed for the used methods and any tests of statistical significance; few of them provide sufficient information on the test design and mention parameters such as *p*-values on their results. The insufficient statistical background of the studies can be clearly seen in the evaluation criteria fulfillment in Table 2.

Conclusion

The study review highly indicates that there are serious annoyance issues which affect acoustic comfort in dwellings. There exist especially problems with impact noise types from neighbors, which include a high degree of low-frequency content. Specifically, walking noise has been reported as the most disturbing noise source. Also, the lack of very low-frequency content in the impact sound measurements leads to weak statistical association with subjective response of residents. Therefore, most studies suggest that measurements should include extended frequencies down to 50 Hz (or even down to 20 Hz), instead of 100 Hz which is the present lowest limit in the ISO standards. The greatest problems with impact noise and related low-frequency transmission are found in LW structures, while concrete buildings have better overall insulation against noise transmission, airborne or impact.

Many studies included in this review lending data to these suggestions lack rigorous scientific presentation of results and statistical methods leading to a risk of misinterpretation. We suggest a harmonized description of methods and results using common acoustic and statistical indicators, sufficient reporting of statistical evaluation parameters, and the testing for statistical significance.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The authors disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This article was written within the research project "Acoustic Comfort in Building Apartments" funded by Saint-Gobain Weber.

References

1. Rindel JH. Acoustic quality and sound insulation between dwellings. *Build Acoust* 1999; 5: 291–301.
2. Rindel JH. Acoustical comfort as a design criterion for dwellings in the future. In: *Proceedings of the sound in the built environment, Aucklandm*, New Zealand, 21–23 November 2002.
3. Rasmussen B and Rindel JH. Sound insulation of dwellings—legal requirements in Europe and subjective evaluation of acoustical comfort. In: *Proceedings of the DAGA'03*, Aachen, 18 March 2003.
4. Rasmussen B and Rindel JH. Concepts for evaluation of sound insulation of dwellings—from chaos to consensus? In: *Proceedings of the 2005 forum acusticum*, Budapest, 29 August–2 September, 2005.
5. Rasmussen B and Rindel JH. Sound insulation between dwellings—requirements in building regulations in Europe. *Appl Acoust* 2010; 71: 373–385.
6. Ljunggren F, Simmons C and Hagberg K. Correlation between sound insulation and occupants perception—proposal of alternative single number rating of impact sound. *Appl Acoust* 2014; 85: 57–68.
7. Ljunggren F, Simmons C and Hagberg K. Findings from the AkuLite project: correlation between measured vibro-acoustic parameters and subjective perception in lightweight buildings. In: *Proceedings of the inter-noise 2013*, Innsbruck, 15–18 September 2013.
8. Hagberg K and Bard D. Low frequency sound transmission in multifamily wooden houses. In: *Proceedings of the inter-noise 2014*, Melbourne, VIC, Australia, 16–19 November 2014.
9. Simmons C and Ljunggren F. Aku20—searching for optimal single number quantities in EN ISO 717—2 correlating field measurements 20—5000Hz to occupant's ratings of impact sounds—new findings for concrete floors. In: *Proceedings of the EURONOISE 2015*, Maastricht, 31 May–5 June 2015.
10. Simmons C, Hagberg K and Backman E. Acoustical performance of apartment buildings—resident's survey and field measurements: AkuLite report 2, 2011, http://www.diva-portal.org/smash/get/diva2:962643/FULLTEXT01.pdf
11. Ljunggren F, Simmons C and Öqvist R. Correlation between sound insulation and occupants perception—proposal of alternative single number rating of impact sound—part II. *Appl Acoust* 2017; 123: 143–151.
12. Ljunggren F, Simmons C and Öqvist R. Evaluation of impact sound insulation from 20Hz. In: *Proceedings of the 24th international congress on sound and vibration, ICSV24*, London, 23–24 July 2017.
13. Guigou-Carter C, Balanant N and Villenave M. Acoustic comfort evaluation in lightweight wood-based buildings. In: *Proceedings of the forum acusticum*, Krakow, 7–12 September 2014.
14. Milford I, Høsøien CO, Løvstad A, et al. Socio-acoustic survey of sound quality in dwellings in Norway. In: *Proceedings of the inter-noise 2016*, Hamburg, 21–24 August, 2016.
15. Høsøien CO, Rindel JH, Løvstad A, et al. Impact sound insulation and perceived sound quality. In: *Proceedings of the inter-noise 2016*, Hamburg, 21 August 2016.
16. Bodlund K. Alternative reference curves for evaluation of the impact sound insulation between dwellings. *J Sound Vib* 1985; 102: 381–402.
17. Bradley JS. Deriving acceptable values for party wall insulation from survey results. In: *Proceedings of the inter-noise 2001*, Hague, 27–30 August 2001.

18. Bradley JS. Acoustical measurements in some Canadian homes. *Can Acoust* 1986; 14(4): 1–40.
19. ASTM E413-16:1999. Classification for rating sound insulation.
20. Hveem S, Homb A, Hagberg K, et al. *Low-frequency footfall noise in multi-storey timber frame buildings*. NKB Nordic Committee on Building Regulations, NKB Committee and Work Reports 1996:12 E, 1997. Helsinki: Monila Oy.
21. Rindel JH and Rasmussen B. Assessment of airborne and impact noise from neighbors. In: *Proceedings of the inter-noise 97*, Budapest, 1997, pp. 1739–1744.
22. Hagberg K. Evaluating field measurements of impact sound. *Build Acoust* 2010; 17: 105–128.
23. Hagberg K. *Ljudkrav mestod av ISO/DIS 717*. Nordic Committee on building Regulations, NKB Committee and Work Reports 1996:02, 1997. Helsinki: Monila Oy.
24. Hongisto V, Mäkilä M and Suokas M. Satisfaction with sound insulation in residential dwellings—the effect of wall construction. *Build Environ* 2015; 86: 309–320.
25. Yeon JY. Subjective evaluation of floor impact noise based on the model of ACF/IACF. *J Sound Vib* 2001; 241(1): 147–155.
26. Yeon JY and Jeong JH. Objective and subjective evaluation of floor impact noise. *J Temp Des Architect Environ* 2002; 2(1): 20–28.
27. Jeon JY, Jeong JH, Vorländer M, et al. Evaluation of floor impact sound insulation in reinforced concrete buildings. *Acta Acust United Ac* 2004; 90: 313–318.
28. Jeon JY, Ryu JK, Jeong JH, et al. Review of impact ball in evaluating floor impact sound. *Acta Acust United Ac* 2006; 92: 777–786.
29. Lee PJ, Kim JH and Jeon JY. Psychoacoustical characteristics of impact ball sounds on concrete floors. *Acta Acust United Ac* 2009; 95: 707–717.
30. Jeon JY and Sato S. Annoyance caused by heavyweight floor impact sounds in relation to the autocorrelation function and sound quality metrics. *J Sound Vib* 2008; 311: 767–785.
31. Jeon JY, Lee PJ, Kim JH, et al. Subjective evaluation of heavy-weight floor impact sounds in relation to spatial characteristics. *J Acoust Soc Am* 2009; 125(5): 2987–2994.
32. Kim JH, Ryu JK and Jeon JY. Effect of temporal decay on perception of heavy-weight floor impact sounds. *J Acoust Soc Am* 2013; 134(4): 2730–2738.
33. Jeon JY and Oh SM. Psychoacoustical evaluation of heavyweight floor impact sounds in apartment buildings. In: *Proceedings of the inter-noise 2014*, Melbourne, VIC, Australia, 16–19 November 2014.
34. Ryu J, Sato H, Kurakata K, et al. Relation between annoyance and single-number quantities for rating heavy-weight floor impact sound insulation in wooden houses. *J Acoust Soc Am* 2011; 129(5): 3047–3055.
35. Gover BN, Bradley J, Schoenwald S, et al. Subjective ranking of footstep and low-frequency impact sounds on lightweight wood-framed floor assemblies. In: *Proceedings of the forum acusticum 2011*, Aalborg, 26 June 2011.
36. Gover BN, Bradley JS, Zeitler B, et al. 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 2011*, Osaka, Japan, 4 September 2011.
37. Späh M, Hagberg K, Bartlomé O, et al. Subjective and objective evaluation of impact noise sources in wooden buildings. *Build Acoust* 2013; 20(3): 193–214.
38. Kylliäinen M, Hongisto V, Oliva D, et al. A laboratory listening experiment on subjective and objective rating of impact sound insulation of concrete floors. In: *Proceedings of the inter-noise 2016*, Hamburg, 21–24 August 2016.
39. Kylliäinen M, Hongisto V, Oliva D, et al. Subjective and objective rating of impact sound insulation of a concrete floor with various coverings. *Acta Acust United Ac* 2017; 103: 236–250.
40. Öqvist R, Ljunggren F and Johnsson R. Listening test of walking noise from 20 Hz in dwellings. In: *Proceedings of the inter-noise 2017*, Hong Kong, China, 27–30 August 2017, pp. 3935–3942.
41. Monteiro C, Machimbarrena M, De la Prida D, et al. Subjective and objective acoustic performance ranking of heavy and light weight walls. *Appl Acoust* 2016; 110: 268–279.
42. Rychtáriková M, Muellner H, Chmelík V, et al. Perceived loudness of neighbour sounds heard through heavy and light-weight walls with equal R_w+ C_(50–5000). *Acta Acust United Ac* 2016; 102(1): 58–66.

43. Rychtáriková M, Roozen B, Müllner H, et al. Listening test experiments for comparisons of sound transmitted through light weight and heavy weight walls. *Akustika* 2013; 19: 1–10.
44. Rychtáriková M, Müllner H, Urbán D, et al. Influence of temporal and spectral features of neighbour's noise on perception of its loudness. In: *Proceedings of the EURONOISE 2013*, Innsbruck, 15 September 2013.
45. Pedersen TH, Antunes S and Rasmussen B. Online listening tests on sound insulation of walls—a feasibility study. In: *Proceedings of the EURONOISE 2012*, Prague, 10–13 June, 2012.
46. Vian J-P, Danner WF and Bauer JW. Assessment of significant acoustical parameters for rating sound insulation of party walls. *J Acoust Soc Am* 1983; 73(4): 1236–1243.
47. Tachibana H, Hamado Y and Sato F. Loudness evaluation of sounds transmitted through walls—basic experiments with artificial sounds. *J Sound Vib* 1988; 127(3): 499–506.
48. Park HK, Bradley JS and Gover BN. Evaluating airborne sound insulation in terms of speech intelligibility. *J Acoust Soc Am* 2008; 123(3): 1458–1471.
49. Park HK and Bradley JS. Evaluating standard airborne sound insulation measures in terms of annoyance, loudness and audibility ratings. *J Acoust Soc Am* 2009; 126(1): 208–219.
50. Hongisto V, Oliva D and Keränen J. Subjective and objective rating of airborne sound insulation—living sounds. *Acta Acust United Ac* 2014; 100: 848–864.
51. Virjonen P, Hongisto V and Oliva D. Optimized single-number quantity for rating the airborne sound insulation of constructions: living sounds. *J Acoust Soc Am* 2016; 140(6): 4428–4436.
52. ISO 12354-1:2017. Building acoustics—estimation of acoustic performance of buildings from the performance of elements—part 1: airborne sound insulation between rooms.
53. ISO 12354-2:2017. Building acoustics—estimation of acoustic performance of buildings from the performance of elements—part 2: impact sound insulation between rooms.
54. ISO 16283-1:2014. Field measurement of sound insulation in buildings and of building elements—part 1: airborne sound insulation.
55. ISO 16283-2:2014. Field measurement of sound insulation in buildings and of building elements—part 2: impact sound insulation.
56. JIS A 1418-2:2000. Acoustic—measurement of floor impact sound insulation of buildings—part 2: method using standard heavy impact sources.
57. ISO 717-1:1996. Acoustics—rating of sound insulation in buildings and of buildings elements—part 1: airborne sound insulation.
58. ISO 717-2:1996. Acoustics—rating of sound insulation in buildings and of buildings elements—2: impact sound insulation.
59. ISO 140-4:1998. Acoustics—measurement of sound insulation in buildings and of building elements—part 4: field measurements of airborne sound insulation between rooms.
60. ISO 140-7:1998. Acoustics—measurement of sound insulation in buildings and of building elements—part 7: field measurements of impact sound insulation of building elements.
61. Höfler M. The Bradford hill considerations on causality: a counterfactual perspective. *Emerg T Epidemiol* 2005; 2005: 2–11.
62. Schünemann H, Hill S, Guyatt G, et al. The GRADE approach and Bradford Hill's criteria for causation. *J Epidemiol Comm Health* 2011; 65: 392–395.
63. Simmons C. Chapter 6. Developing a uniform questionnaire for socio-acoustic surveys in residential buildings. In: Fausti P, Carrascal T, Ingelaere B, et al. (eds) *Building acoustics throughout Europe, vol. 1: towards a common framework in building acoustics throughout Europe*. 2013, pp. 102–124.
64. ISO/TS 15666:2003. Acoustics—assessment of noise annoyance by means of social and socio-acoustic surveys.

Paper B

Soundscapes of Buildings and Built Environments

BUILDING ACOUSTICS

Building Acoustics
1–22

Reprints and permissions:
sagepub.co.uk/journalsPermissions.nav
DOI: 10.1177/1351010X18772026
journals.sagepub.com/home/bua
SAGE

Review of acoustic comfort evaluation in dwellings: part II—impact sound data associated with subjective responses in laboratory tests

Nikolaos-Georgios Vardaxis and Delphine Bard

Abstract

The concept of acoustic comfort is hardly defined and used to refer to conditions of low noise levels or annoyance based on standardized descriptors. Airborne and impact sound measurements are used to rate acoustic comfort in dwellings, but they often do not express human perception of noise or comfort. If the descriptors are statistically associated with self-reported responses, they can be used as prediction models and considered sufficient for acoustic comfort assessment. This review article presents studies that approach acoustic comfort in dwellings via the association of acoustic data and subjective responses in laboratory tests. Specifically, we investigate the cases of impact sound, since it is usually reported as the most disturbing noise source in dwellings. We also evaluated the reviewed studies with the Bradford Hill's criteria. The reviewed studies indicate that self-reported annoyance to impact sound is an important issue and it can be predicted well in overall. Various standardized descriptors are studied and associate sufficiently with subjective responses. Inclusion of low frequencies down to 50 Hz in measurements improves the association of impact sound descriptors to subjective responses. Some impact noise stimuli associate only with some descriptors but not all. From the standardized impact sources, the tapping machine is the most efficient to predict overall annoyance and the impact ball for human walking or typical impact sounds in dwellings.

Keywords

Acoustic comfort, impact sound, laboratory, subjective responses, association, evaluation

Introduction

This article concerns a review of acoustic comfort evaluation for dwellings in laboratory tests. The reviewed publications present studies which were conducted in laboratory conditions and evaluate

Division of Technical Acoustics, Department of Construction Sciences, Faculty of Engineering, LTH, Lund University, Lund, Sweden

Corresponding author:
Nikolaos-Georgios Vardaxis, Division of Technical Acoustics, Department of Construction Sciences, Faculty of Engineering, LTH, Lund University, Lund 221 00, Sweden.
Email: nikolas.vardaxis@construction.lth.se

the association of acoustic data with subjective responses and thus approach acoustic comfort perception. Since impact sound has been reported in the literature as the most important noise source in dwellings,[1] this review is focused only on impact sound studies and results. The examined laboratory tests usually include acoustic data of measured sound insulation or recorded noise sounds of various types, which are deployed in controlled listening experiments where the subjects, that is, the participants, offer their self-reported responses.[2–15] In some of the presented cases, the acoustic data of the reviewed studies originate from field measurements or sound recordings in real buildings and not laboratory measurements. However, those data are still processed and used for listening experiments within a laboratory setup under controlled conditions in the reviewed studies.

Acoustic comfort is vaguely defined in the literature, despite being an important concept in engineering. It is typically used to denote a state of low or no noise and therefore lack of annoyance for the residents. A complete definition is provided in Rasmussen and Rindel[1] as "a concept that can be characterized by absence of unwanted sound, desired sounds with the right level and quality, opportunities for acoustic activities without annoying other people."

Standardized measurements and relevant descriptors are used to assess building acoustic conditions. They do not always represent well how people perceive the living sound environment as occupants in their flats. Previous studies have shown that residents suffer from impact noise types: such noise types have dominant low-frequency characteristics which are usually neglected in a standardized measurement with a typical frequency range of 100–3150 Hz. Also, the impact sound sources used during measurements might offer different types of excitation than the real-life impact sounds. Then, there are various types of building constructions and components, which provide different structural and acoustical conditions to the tenants.[3–15]

Therefore, it is important to test the association of the acoustic data from measured results to self-report responses; that association is tested with statistical analyses comparing objective and subjective data in many studies in this review. Sometimes, alternative versions of standardized descriptors are suggested in order to achieve better agreement of acoustic data with subjective responses. If a strong association can be established, then it is possible to formulate models for prediction of annoyance and comfort for the residents.

The understanding of acoustic comfort and development of prediction models would be essential for the design of proper acoustic conditions in buildings. For all the above reasons, comparing measured data to human perception is essential for the characterization of acoustic comfort in overall. In this review article, a set of selected studies are presented dealing with impact sound data compared and associated with subjective responses collected in laboratory tests.

Methods

A wide search for peer-reviewed publications and conference proceedings, which include examination between acoustic data and self-reported responses relevant to impact sound, has been done in the following databases: ScienceDirect, AIP Scitation, Ingenta Connect, ResearchGate, PubMed, Scopus, and Google Scholar. The search strategy included numerous searches in the databases using relevant keywords, such as objective, subjective, acoustic, psychoacoustic, self-report, rating, score, comfort, quality, impact, sound, insulation, noise, annoyance, assessment, association, and correlation. Several publications were subsequently found as references of the first selected papers.

Finally, this review article includes 10 Asian studies,[2–11] 1 Canadian study,[12,13] and 4 European studies.[14–17] Requirements for inclusion of papers in this review were the comparison of results between impact sound measured data and subjective responses collected from tests in laboratory experiments. Overall, 37 papers were found during the search in databases or relevant references and were evaluated by title name, abstract reading full reading; 17 of them were included in this review. The selection was based on their relevance to this review: some publications did not offer statistical comparisons or did not consider impact sound laboratory tests and thus were exclu ded.[18–37] Other exclusion criteria were the year of publication and language: only articles published after 2000 in English were included. The bibliographic research took place between April 2015 and September 2017.

Summary of methods, metrics, and quantities in the reviewed studies

Many different indicators (or descriptors) have been used to represent different quantities in acoustic measurements. They are all standardized in international ISO standards or other compliable national standards. Many variations of them exist as well, since experimental research has been done to acquire better indicators than the standardized ones. A description of all indicators involved in this review is presented in Table 1. For the full methods used to acquire and calculate the indicators, please see the relevant standards.

Several statistical methods such as analysis of variance (ANOVA), regression analysis, and principal component analysis (PCA) associate acoustic data to subjective responses. Details on the statistical methods can be found in relevant literature. The quality of statistical association is usually described with typical parameters such as the correlation coefficient, denoted as r, ρ, or R, and the coefficient of determination, denoted as R^2. The p values and the confidence intervals (CIs) are measures of statistical significance.

Evaluation of included studies

The quality of evidence for studies in this review was evaluated Bradford Hill's criteria[26] which is an evidence classification method often used in epidemiology and health review studies. The fulfilled criteria are rated in a scale of High (+++), Moderate (++), and Low (+). The evaluations are tabulated in Table 2, while the criteria are as follows.

Strength of association: it refers to the causality proven by the association between the studied variables (cause, effect size, and confounding factors).

Consistency: it indicates the degree of certainty when similar results are observed by different studies in different tests.

Specificity: specific factors and effects on a specific population lead to a more likely causal relationship.

Temporality: it is based on temporal relations between effects and used as an indicator for causality, meaning one effect happening after an exposure.

Biological gradient: it refers to the relation between exposure and effect; usually bigger exposure leads to greater effect, but not always, while the opposite outcome can happen as well.

Plausibility: it means that a biological explanation of why a cause leads to a certain effect supports a reasonable causality.

Coherence: it is a condition meaning that a stated causal relationship should not contradict with other accepted results or knowledge.

Experiment: it refers to the study design parameters that guarantee a reasonable causation, like randomization.

Table 1. List of acoustic indicators used in the review studies.

Indicator	Description	Standards	References
ACF	Autocorrelation function: correlation of a time signal with delayed versions of itself	–	2,3,7
IACC	Interaural cross-correlation function: covariance of delayed versions of the left and right ear time signal	–	2,3,8
L	Loudness: sound quality (SQ) metric defined by Zwicker & Fastl	ISO 532:1975	3,6,7,11,38,39
N_5, N_{10}	Percentile loudness: SQ metric defined by Zwicker & Fastl	–	5,6,11,39
N_{max}	Maximum loudness: SQ metric defined by Zwicker & Fastl	–	6,39
FS	Fluctuation strength: SQ metric defined by Zwicker & Fastl	–	3,7,39
T	Tonality: SQ metric defined by Zwicker & Fastl	–	3,6,39
UA	Unbiased annoyance: SQ metric defined by Zwicker & Fastl	–	3,39
S	Sharpness: SQ metric defined by Zwicker & Fastl	–	6,39
R	Roughness: SQ metric defined by Zwicker & Fastl	–	6,39
SPL	Sound pressure levels		5,8,9,10
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	4,5,40,41
L_{Amax}	Maximum A-weighted sound pressure level	JIS A 1418, KS F 2810-2	4,5,8,9,10,11,40,42
$L_{i,Fmax,\ AW}$	Maximum A-weighted impact source level	JIS A 1418, KS F 2810-2	6,8,9,10,11,12,13,40,42
DR	Decay rate: similar to reverberation time but for impact sounds		8,9,10
JND	Just noticeable difference		7,8,9
$L_{n,w}$	Impact sound insulation index characterizing a building element (laboratory measurements)	ISO 717-2, ISO 140-7, EN ISO 12354-2, ISO 16283-2	12,13,41,43,44,45
$L'_{n,w}$	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	14,15,16,17, 41,43,44,45
C	*C* is an A-weighted pink noise spectrum adaptation term	ISO 717-1, 717-2, EN ISO 12354-1, 12354-2	12,13,14,15,16,17,41,43,44

Analogy: the possibility of having or predicting analogous effects from similar factors without total evidence.

Publication type: an additional criterion in order to rank the reviewed studies. Scientific journal papers are thoroughly peer reviewed, while conference papers are usually less well reviewed. There are study reports from research organizations that may be scientifically well

Table 2. Evaluation of the presented studies according to selected criteria.

Reference number	Publication type[a]	Strength of association	Consistency	Specificity	Temporality	Biological gradient	Plausibility	Coherence	Experiment design	Analogy
Yeon[2]	++	+	++	+	+	++	++	+	++	++
Yeon and Jeong[3]	+++	+	+	+	+	+	+	+	++	+
Jeon et al.[4]	+++	++	++	++	++	+++	++	++	++	++
Jeon et al.[5]	+++	++	++	++	++	++	++	++	++	++
Lee et al.[6]	+++	+++	+++	+++	+++	++	++	+++	+++	+++
Jeon and Sato[7]	+++	++	++	++	++	++	++	++	++	++
Jeon et al.[8]	+++	++	+++	++	+++	++	++	++	++	++
Kim et al.[9]	+++	++	++	++	+	+	++	+	+	++
Jeon and Oh[10]	++	+	+	+	+	++	+	+	+	+
Ryu et al.[11]	+++	++	++	+	++	+	+	++	+	+
Gover et al.[12]	++	+	++	++	++	+	++	++	++	++
Gover et al.[13]	++	+	++	++	++	+	++	++	++	++
Späh et al.[14]	+++	++	++	++	++	++	++	++	++	++
Kylliäinen et al.[15]	++	++	++	++	++	+++	++	++	+++	++
Kylliäinen et al.[16]	+++	++	++	++	++	+++	++	++	+++	++
Öqvist et al.[17]	+++	+++	++	++	++	++	++	++	+++	++

[a]Types: scientific journal (+++), conference paper (++), and report (+).

conducted but not reviewed at all. There are others, for example, unofficial reports, which are excluded. Thus, publications were evaluated as scientific journal (+++), conference paper (++), and report (+).

The included studies were evaluated by the authors of this article, while the presented data were chosen according to their relation and importance for this review's context. In Table 3, an overview of all the selected studies can be found, which are tabulated with summary of results, study design, methods, and conclusions. In Table 2, the evidence evaluation rating of the studies is presented according to the above criteria. Readers who would like to have a deeper insight into any specific study results or conclusions may read the original publications using the references. Essential information might also be missing from this review if they are not reported in the papers. The studies are presented in chronological order and analyzed in the next chapter.

Results: associations of impact sound acoustic data with self-reported responses in laboratory tests

In Yeon,[2] a laboratory listening test with 20 participants (aged 21–31 years) to investigate the differences in perception of impact noise sounds was recorded in apartments. The standardized sources were a bang machine (tire) and a tapping machine. The subjects listened to the samples and had to adjust them to pink noise levels according to their perception of loudness and noisiness. First, the results of loudness and noisiness matching were highly and significantly correlated ($r=0.916$, $p<0.01$). The subjects raised the pink noise 2–3 dB higher to match the levels of the bang machine, while they lowered the pink noise 3–4 dB to match the tapping machine sound: subjects perceived bang machine 6–7 dB noisier and louder than the tapping machine as the author comments. Also, parameter values of the autocorrelation function (ACF) and the interaural cross-correlation function (IACC) were analyzed for both sources. The maximum amplitude Φ (0) of the ACF is reported as highly correlated to perceived noisiness of the tapping machine noise. The author argues that perceived loudness and noisiness can be explained by the ACF and directivity of peaks by the IACC. However, this is not supported by any statistical testing, as only correlations among acoustic parameters are presented.

In Yeon and Jeong,[3] a continuation of the previous study is presented as the evaluation of loudness. A typical concrete floor structure in a Korean residential building and nine different configurations with treatments of that structure were measured according to JIS A 1418.[18] Recordings were made for the impact excitation sources: tapping, bang machine, rubber impact ball, and human jumping. A listening test with 30 subjects (27 males, 3 females, aged 24–41 years) was conducted where the test samples were evaluated in a pair of comparison test (108 comparisons) using a 5-point scale (−1, −0.5, 0, 0.5, and 1). Subjective responses of loudness were highly correlated with the maximum ACF amplitude Φ (0) of tapping noise ($r=0.96$, $p<0.01$), bang machine noise ($r=0.94$, $p<0.01$), and impact ball noise ($r=0.94$, $p<0.01$). The same applied to the subjective loudness responses associated with Zwicker's parameters: Loudness (L) and unbiased annoyance (UA), which are psychoacoustic metrics defined in literatures.[18,19] Specifically, the loudness responses correlated highly with L for tapping noise ($r=0.94$, $p<0.01$), sufficiently for bang machine noise ($r=0.74$, $p<0.01$), and highly for impact ball noise ($r=0.94$, $p<0.01$). They also correlated highly with UA for tapping noise ($r=0.92$, $p<0.01$) and sufficiently for bang noise ($r=0.72$, $p<0.01$) and rubber ball noise ($r=0.76$, $p<0.01$). Also, L values were highly correlated to UA. The authors highlight that Zwicker parameters are more reasonable for the tapping machine noise; for the bang machine and impact ball cases, maximum amplitude Φ (0) was associated with the loudness perception more than other parameters.

Table 3. Overview of studies' summaries.

Reference number	Samples and experiment details	Variables as defined in studies	Models and results	Parameters for evaluation	Summary of results
Yeon[2]	20 subjects in a listening test (age = 21–31 years)	*Independent*: In situ sound recordings of impact sources: – bang machine (tire) – tapping machine *Dependent*: V1: subjective loudness and noisiness	Test samples matching to pink noise in steps of 3 dB	No details provided	– Bang machine was perceived 6–7 dB noisier and louder than the tapping machine, which is too loud for an impact source. – ACF magnitude Φ (0) important for loudness and noisiness perception
Yeon and Jeong[3]	30 subjects in a listening test (27 males, 3 females, age = 24–41 years)	*Independent*: In situ sound recordings of impact sources: – Bang machine (tire) – Tapping machine – Impact rubber ball ACF/IACC Zwicker parameters *Dependent*: SV: Subjective loudness	*Correlations*: – Tapping machine noise *SV* to $\Phi(0)$; *SV* to *L*—loudness; *SV* to *UA*—unbiased annoyance; – Bang machine noise *SV* to $\Phi(0)$; *SV* to *L* —loudness; *SV* to *UA*—unbiased annoyance; – Impact rubber ball noise *SV* to $\Phi(0)$: *SV* to *L*—loudness: *SV* to *UA*—unbiased annoyance: *Multiple regression models*: $SV_{tapping} = -17.761 + 0.065\ \Phi(0) + 11.51\ \tau_1 - 1.45\varphi_1$ $SV_{tapping} = -5.731 + 0.25L + 2.23FS + 1.16T - 0.0076\ UA$ $SV_{Bang} = -3.691 + 0.147\ \Phi(0) - 0.251\ \tau_e - 3.83\ W_{IACC}$ $SV_{Bang} = -0.534 + 0.22L$ $SV_{Ball} = -4.754 + 0.121\ \Phi(0) – 0.2021\ \tau_e - 1.01\ IACC + 0.992\ \tau_{IACC}$ $SV_{Ball} = -1.431 + 0.177L + 0.24FS - 0.0012UA$	*Coefficients (all $p < 0.01$)*: $\gamma = 0.96$ $\gamma = 0.94$ $\gamma = 0.92$ $\gamma = 0.94$ $\gamma = 0.74$ $\gamma = 0.72$ $\gamma = 0.94$ $\gamma = 0.94$ $\gamma = 0.76$ *Total coefficients (all $p < 0.05$):* $\gamma = 0.94$ $\gamma = 0.98$ $\gamma = 0.96$ $\gamma = 0.74$ $\gamma = 0.98$ $\gamma = 0.95$	– Subjective response of loudness was highly correlated with the maximum ACF amplitude Φ (0) for all impact sources – Subjective response of loudness was highly correlated with Zwicker's Loudness and Unbiased annoyance. – Zwicker parameters are more reasonable for the tapping machine noise while for the bang machine and impact ball cases Φ (0) seems to affect more the loudness perception. – Spatial factors, pitch and sound energy are also significant parameters as indicated by the multiple regression models
Jeon et al.[4]	60 subjects in a listening test (30 Korean, 30 German) 56 sound samples tested	*Independent*: Two standardized impact sources: S1: tapping machine L_{eq} S2: tire machine L_{max} Measured and recorded below of eight types of floor structures in various configurations with insulation in the sending room *Dependent:* V1: loudness responses V2: annoyance responses	*Correlations*: – V1 (loudness) to: L_{eq} (S1) L_{max} (S2) – V2 (annoyance) to: L_{eq} (S1) L_{max} (S2) – Impact noise differences: ΔdB	*Coefficients*: $R^2 = 0.64$ above 250 Hz $R^2 = 0.49–0.81$ above 63 Hz $R^2 = 0.36$ above 250 Hz $R^2 = 0.25–0.49$ above 63 Hz $R^2 = 0.55$ for Koreans $R^2 = 0.55$ for Germans	– Good ratings for the cases of sending rooms with insulation on floor and walls and for the extra suspended ceiling insulation. – Good associations in general above 250 Hz for the tapping machine and slightly good above 63 Hz for the tire machine. – Koreans are more sensitive to impact sounds due to bigger exposure

(Continued)

Table 3. (Continued)

Reference number	Samples and experiment details	Variables as defined in studies	Models and results	Parameters for evaluation	Summary of results
Jeon et al.[5]	30 subjects (students) in a listening test 48 sound samples tested Additional 98 subjects in on-site auditory experiment and 10 subjects in a listening experiment combined	*Independent*: Two standardized impact sources: S1: impact ball S2: tapping machine Measured and recorded below of eight types of floor structures in various configurations with insulation in the sending room *Dependent:* V1: loudness responses	*Regression models*: – V1 (loudness) to: Mean *SPL* L_{Amax} $Inverse - A$ $L_{n,w} + C_{I,63-2000}$ *Loudness* *Percentile loudness* N_{10}	*Coefficients*: S1: $R^2=0.57$, S2: $R^2=0.84$ S1: $R^2=0.70$, S2: – S1: $R^2=0.69$, S2: $R^2=0.79$ S1: –, S2: $R^2=0.73$ S1: $R^2=0.74$, S2: $R^2=0.84$ S1: $R^2=0.77$, S2: $R^2=0.88$	– Tapping machine offers better association with subjective ratings than impact ball; – The impact ball spectra were found to be the most similar to real impact sounds in multistory residential buildings. – Three classes were suggested according to the $L_{i,Fmax,AW}$ levels: Class 1 (<44 dB), Class 2 (<49 dB) and Class 3 (<54 dB)
Lee et al.[6]	40 subjects in a listening test (28 males and 12 females, age = 24–35 years) 54 sound samples tested	*Independent*: Impact ball excitation measured and recorded below of 35 floor structures. Descriptors used: $L_{i,Fmax,AW}$, $L_{-number}$, L_{Aeq} L_{Amax}, LL_Z, N_{max}, N_5, $L_{1/1(63-500\,Hz)}$, *ASEL* V1: annoyance responses in pairwise comparisons	*Regression models*: – V1 (annoyance) to: LL_Z L_{Amax} $L_{i,Fmax,AW}$ Loudness (L) Fluctuation strength (F) Multiple linear regression: $SV_{annoyance} = 0.77L + 0.15F$	*Coefficients*: $r=0.97$, $R^2=0.94$, $p<0.05$ $r=0.92$, $R^2=0.85$, $p<0.01$ $r=0.88$, $R^2=0.77$, $p<0.01$ $r=0.81$, $R^2=0.66$, $p<0.01$ $r=0.90$, $R^2=0.81$, $p<0.05$ $r=0.90$, $R^2=0.81$, $p<0.05$	– Very good correlation with all metrics tested; L_{Amax} is suggested as the most practical descriptor. Sound quality metrics are difficult to derive. – Three dimensions revealed in a factor analysis; “1: reverberance and spaciousness,” “2: dullness,” and “3: loudness”
Jeon and Sato[7]	40 subjects in a listening test (20 students and 20 housewives) 28 pairs of sound samples tested	*Independent*: Impact ball and bang machine excitation measured and recorded below of six floor structures. *Descriptors*: $L_{i,Fmax,AW}$, ACF, and SQ metrics *Dependent*: V1: annoyance	*Correlations*: – V1 (annoyance) to $\Phi(0)$ $VAR\_\Phi(0)$ VAR_φ_1 Loudness (L) Fluctuation strength (F) *Multiple regression models*: $SV_{annoyance} \approx 0.61\Phi(0) + 0.15VAR\_\Phi(0) - 0.46VAR\_\varphi_1$ $SV_{annoyance} = 0.63L + 0.34F$	*Coefficients*: $r=0.66$ $r=0.13$ $r=-0.29$ $r=0.66$ $r=0.38$	– Sound energy amplitude $f(0)$ and loudness were the best correlated to subjective annoyance. – ACF parameters can be useful for prediction of subjective annoyance

Table 3. (Continued)

Reference number	Samples and experiment details	Variables as defined in studies	Models and results	Parameters for evaluation	Summary of results
Jeon et al.[8]	20 subjects in a listening test (age = 24–35 years) 87 impact ball recordings processed to 9 sound stimuli for the test	*Independent*: Impact ball excitation measured and recorded in real floor structures. *Dependent*: V1: Just noticeable differences (JND); V2: Annoyance responses in pairwise comparisons Descriptors used: L_{Amax}, SPL, IACC	*Multiple regression models*: – V2 (annoyance) to $SV_{annoyance} \approx -0.34(IACC) + 0.95(SPL)$	*Individual coefficients:* $p < 0.01$ *Total coefficients*: $r = 0.78$, $R^2 = 0.61$, $p < 0.01$	– The JND for the SPL was found 1.5 dB in terms of L_{Amax} and for the IACC levels between 0.12 and 0.13 – The annoyance ratings increased as IACC decreased and SPL increased; both measures contributed to the regression model significantly – Also, SPL and temporal variance of IACC were found to contribute independently to annoyance
Kim et al.[9]	20 subjects (age = 20–35 years) 92 impact ball recording transformed to 24 test sound samples	*Independent*: Impact ball test samples. *Dependent*: V1: Just noticeable differences (JND) of decay rate (DR) V2: Annoyance responses in pairwise comparisons Descriptors used: L_{Amax} (SPL), DR30	Pairwise comparison test between samples *Multiple regression models*: – V2 (annoyance) to $SV_{annoyance} = -0.02DR + 0.18SPL - 8.21$ *Linear regression* – V2 (annoyance) to $L_{A,Fmax}$ $L_{i,Fmax,c}$ (with correction)	 *Total coefficient*: $r = 0.84$ ($R^2 = 0.71$, $p < 0.01$) $r = 0.81$, $R^2 = 0.65$ $r = 0.99$, $R^2 = 0.98$	– JND of DR30 was found at a difference of 11 dB/s between test sound and reference. – SV increases when both SPL and DR increase. – Longer DR30 causes higher annoyance with constant SPL. – Louder stimuli cause higher annoyance with constant DR. – Suggested correction to SPL considering the DR increases association of SPL to annoyance
Jeon and Oh[10]	30 subjects (age = 20–35 years) 28 impact ball recorded sound stimuli	*Independent*: Impact ball test samples. *Dependent:* V1: Annoyance responses in pairwise comparisons V2: Acceptability descriptors used: L_{Amax} (SPL), DR30, DR60	Rating in 7-point scale for sound samples	*Dose-response curves provided in paper* No further statistical details	– No significant differences between DR30 and DR60 below 61 dBA—Some very significant above 67 dBA ($p < 0.01$). – Sounds evaluated with DR30 were rated as more annoying than DR60, thus above 60 dBA there is a significant effect. – The acceptable limit for impact sound in terms of LA_{max} was found at circa 50 dBA – A classification system for annoyance to impact sounds is developed

(Continued)

Table 3. (Continued)

Reference number	Samples and experiment details	Variables as defined in studies	Models and results	Parameters for evaluation	Summary of results
Ryu et al.[11]	17 subjects in a listening test (age circa 20 years)	*Independent*: Impact ball and bang machine excitation measured and recorded in real floor structures. *Dependent:* V1: annoyance responses in pairwise comparisons	*Correlations*: – Part 1: V1 (annoyance) to: $L_{i,Favg,Fmax}$ N_5 – Part 2: V1 (annoyance) to: $L_{i,Favg,Fmax}$ N_5	*Coefficients*: $r = 0.96$, $p < 0.01$ $r = 0.96$, $p < 0.01$ $r = 0.84$, $p < 0.01$ $r = 0.74$, $p < 0.01$	– Arithmetic averages of octave-band *SPL* like $L_{i,Favg,Fmax}$ and Zwicker's loudness percentile N_5 predict very well the subjective annoyance
Gover et al.[12,13]	12 subjects in a listening test 90 sound samples tested	*Independent*: Two impact noise types: S1: adult walking barefoot S2: impact ball Measured and recorded below of 19 types of lightweight floor-ceiling structures *Dependent*: V1: relative annoyance responses in pairwise comparisons	*Correlations*: V1 (annoyance) to $L_{n,w}$ $L_{n,w} + C_{I,50-2500}$ $L_{n,w} + C_{I,100-2500}$ $L_{i,Fmax,r}$ $L_{i,Fmax,AW}$ $L_{i,Fmax(63-1kHz)}$	*Coefficients*: S1: $R^2 = 0.85$, S2: $R^2 = 0.89$ S1: $R^2 = 0.87$, S2: $R^2 = 0.90$ S1: $R^2 = 0.83$, S2: $R^2 = 0.96$ S1: $R^2 = 0.70$, S2: $R^2 = 0.86$ S1: $R^2 = 0.80$, S2: $R^2 = 0.93$ S1: $R^2 = 0.80$, S2: $R^2 = 0.93$ Most differences between sound ratings statistically significant ($p < 0.05$)	– The standard tapping machine outcome was the best associated with the subjective ratings; it can be used adequately for subjective annoyance prediction – The rubber impact ball offered very good results as well
Späh et al.[14]	40 subjects in two similar listening tests	*Independent*: Impact sources: tapping machine, impact ball excitation measured, and human walking recorded in real and laboratory setups of floor structures. *Dependent*: V1: annoyance responses in a scale 0–10	*Correlations*: V1 annoyance to walking: $L'_{nT,w}$ $L'_{nT,w} + C_{I,50-2500}$ $L'_{n,w} + C_{I,50-2500}$ $L'_{nT,\,Hagberg\,03}$ $L'_{nT,\,Hagberg\,04}$ $L'_{nT,\,Bodlund}$ V1 annoyance to moving chair noise: $L'_{nT,w} + C_{I,50-2500}$ $L'_{nT,\,Bodlund}$ $L'_{n,TA\,20-2500}$ $L'_{n,TA\,50-2500}$ $L'_{nT,w} + C_{I,50-2500}$	*Coefficients*: $r = 0.62$, $R^2 = 0.38$ $r = 0.76$, $R^2 = 0.58$ $r = 0.78$, $R^2 = 0.61$ $r = 0.79$, $R^2 = 0.63$ $r = 0.79$, $R^2 = 0.62$ $r = 0.77$, $R^2 = 0.58$ $r = 0.85$, $R^2 = 0.72$ $r = 0.85$, $R^2 = 0.73$ $r = 0.91$, $R^2 = 0.82$ $r = 0.92$, $R^2 = 0.84$ $r = 0.91$, $R^2 = 0.82$	– The tapping machine represents poorly walking annoyance – The Japanese impact ball is the most appropriate source to represent walking noise annoyance due to frequency spectrum similarities; the modified tapping machine offered slightly better associations but it is considered impractical. – Measuring down to 50 Hz helps to acquire good associations with subjective annoyance

Table 3. (Continued)

Reference number	Samples and experiment details	Variables as defined in studies	Models and results	Parameters for evaluation	Summary of results
Kylliäinen et al.[15,16]	55 subjects in a listening test (25 males, 30 females, age = 25–57 years, mean = 27 years) 54 sound samples tested	*Independent*: five sound samples of impact noise types: S1: walking with hard shoes; S2: walking with socks; S3: walking with soft shoes; S4: bouncing ball; S5: moving chair; filtered through nine types of floor impact SRI spectra. *Dependent*: V1: loudness responses V2: annoyance responses	*Regression models*: – V1 (loudness) to $L'_{n,w} + C_{I,50-2500}$ $L'_{n,w} + C_I$ – V2 (annoyance) to $L'_{n,w} + C_{I,50-2500}$	*Coefficients*: $R^2 = 0.56$ (S1) $R^2 = 0.37$ (S3) $R^2 = 0.53$ (S5) $R^2 = 0.57$ (S1) $R^2 = 0.39$ (S3) $R^2 = 0.50$ (S5) $R^2 = 0.49$ (S1) $R^2 = 0.31$ (S3) $R^2 = 0.47$ (S5) All $R^2 > 0.12$ statistically significant ($p < 0.01$)	– $L'_{n,w} + C_I$, $L'_{n,w} + C_{I,50-2500}$, $L'_{n,w,Fas}$, $L'_{n,w,Fas,50}$, $L'_{n,w,Ger}$, and $L'_{n,w,Bod}$ were found to be the best indicators for both subjective loudness and annoyance – Low frequencies 50–100 Hz inclusion in the SNQs offers better correlation to the subjective responses
Öqvist et al.[17]	24 subjects in a listening test (12 males, 12 females, age mean = 27 years, SD = 5 years) 4 sound samples tested	*Independent*: two sound samples of impact noise types: walking with socks, walking with hard shoes, recorded under two floors: a lightweight (LW) a concrete heavyweight (HW) *Dependent*: V1: annoyance responses	Pairwise comparison test between samples	No details provided	– Annoyance perception was significantly higher for the lightweight floor case – 20 Hz was indicated as the limit for perceived annoyance, as an important limit to evaluate walking with socks and impact sounds in LW

SD: standard deviation; SPL: sound pressure level; SRI: Sound Reduction Index; SNQ: single number quantities.

Furthermore, a multiple regression analysis was done which resulted in the following optimal models for the loudness perception, denoted as SV, all with statistical significance ($p<0.05$). For the tapping machine case, the model was $SV_{\text{tapping}}=-17.761+0.065\ \Phi(0)+11.51\,\tau_1-1.45\varphi_1$, where τ_1 and φ_1 are parameters (for time and amplitude, respectively, at 1 ms) of the ACF. The total correlation coefficient of the model was $r=0.94$. Another model was acquired using all the examined Zwicker parameters: $SV_{\text{tapping}}=-5.731+0.25\,L+2.23\,FS+1.16\,T-0.0076\,UA$, where FS and T denote Fluctuation Strength[19] and Tonality,[19] respectively, with total $r=0.98$. The authors highlight that pitch and energy changes are important parameters.

For the case of bang machine noise, the derived models were $SV_{Bang}=-3.691+0.147\ \Phi(0)-0.251\,\tau_e-3.83\ W_{IACC}$ ($r=0.96$) and $SV_{Bang}=-0.534+0.22\ L$ ($r=0.74$). The term τ_e denotes the effective duration of the envelope of normalized ACF and W_{IACC} is the width of IACC at time τ_{IACC} (inter-aural delay time), see details in Yeon and Jeong.[3] Finally, for the impact ball noise, the models were $SV_{Ball}=-4.754+0.121\ \Phi(0)-0.2021\ \tau_e-1.01\ IACC+0.992\tau_{IABC}$ ($r=0.98$) and $SV_{Ball}=-1.431+0.177\ L+0.24\ FS-0.0012\ UA$ ($r=0.95$). Thus, the authors highlight the spatial factors and sound energy as important parameters for the sources: impact ball and bang machine.

Similar studies regarding floor impact sound and self-reported loudness and annoyance were continued in study.[4] Eight floors in different apartments (same floorplan) of an unoccupied multistory building in Seoul were measured following the standard JIS A 1418. Different configurations in the sending rooms including insulation for the floor, walls, and ceiling were tested with two different impactors, the tapping machine and the tire machine measured in L_{Aeq} and L_{Amax}, respectively. Sound recordings using a dummy head were taken as well, which were used in an auditory test with 60 participants (30 Korean and 30 German). The sound samples of the floor setups were tested in pairs, always using a floor structure with no additional insulation as a reference sound to be compared with the other seven floor types. Overall, 56 sound stimuli were tested in the listening experiment, and 28 initial pair of sounds were tested twice and in random orders. The participants had to rate loudness (in a scale from −2 to 2, 0 means equal loudness between stimuli) and annoyance (scale 1–9) for each pair of stimuli.

Lower levels of subjective loudness and annoyance were reported for the cases of sending rooms with insulated floor and walls or the same setup with an extra suspended ceiling insulation. These conclusions were made for both cases of impact noise sources. In this study, the parameter of different culture is featured as well. A comparison of impact noise level differences and subjective data offered determination coefficient values R^2 equal to 0.55 for the Korean and 0.86 for the German subjects; the results for Koreans are not so consistent due to higher impact noise sensitivity according to the authors. Also, correlation coefficients, dependent on frequency (1/3 octave bands) are presented for the data comparison; good correlations were found in general above 250 Hz for the tapping machine around 0.8 for loudness ($R^2=0.64$) and 0.6 for annoyance ($R^2=0.36$) and above 63 Hz for the tire machine with values between 0.7 and 0.9 (R^2: 0.49–0.81) for loudness and 0.5 and 0.7 for annoyance (R^2: 0.25–0.49). It is highlighted that the tire machine spectrum has dominant frequencies below 250 Hz and that could be reduced on thicker concrete slabs.

A continuation of the same study in Korea is presented in Jeon et al.[5] Further measurements in the test building and floor structure configurations were conducted for another comparison of two impact sources: impact ball and tapping machine. A total of 30 students took part in a similar listening experiment rating 48 sound samples in the same loudness scale (–2 to 2). Several descriptors were tested for the association with subjective ratings. For the impact ball case, the results were sufficient with coefficients acquired by L_{Amax}, Zwicker's Loudness L, and Percentile Loudness N_{10} offering R^2 of 0.70, 0.74, and 0.77, respectively. However, L_{Amax} is still suggested as a practical descriptor since the authors highlight that Zwicker's parameters are not easy to determine due to instrumentation and calculations. For the tapping machine, the results were very good with R^2

of 0.84, 0.84, and 0.88 for mean sound pressure level (SPL) averaged for all measured structures L and N_{10}, respectively.

Two additional listening experiments were conducted in this study[5] with few details provided:

1. An on-site auditory experiment with 98 subjects in a living room of the test building to rate annoyance (scale 1–9) to impact ball sounds dropped from various heights. Three categories were suggested for classification using this scale: "Audibility" (1–3), "Disturbance" (4–6), and "Amenity" (7–9). The level of $L_{i,Fmax,AW} = 54\,\text{dB}$ corresponded to a level of annoyance of 4 in the rating scale. Three classes were suggested according to the $L_{i,Fmax,AW}$ levels: Class 1 (<44 dB), Class 2 (<49 dB), and Class 3 (<54 dB).
2. A listening test with 10 students was conducted to investigate the just noticeable differences (JND) for the perception of impact ball noise in SPL. The JND level was recognized at about 2 dB for both the tapping machine and the impact ball cases, as indicated by 86% and 89% of the participants in each case, respectively.

In a further study in South Korea,[6] impact ball sounds were again recorded in 35 different typical apartments (100–120 m²), which were box-frame-type reinforced concrete constructions with slab thickness 150–180 mm. They were clustered in three groups based on their frequency characteristics and they were then used for two auditory experiments with 40 participants (28 males, 12 females, age span 24–35 years). The first experiment concerned successful indicators of perceived annoyance; 87 impact ball sound samples (SPL between 38 and 64 dB, divided in three groups) were evaluated in pair comparisons. The sound quality (SQ) metrics reported and used for the assessment were $L_{i,Fmax,AW}$, $L_{-number}$, L_{Aeq}, L_{Amax}, LL_Z (Zwicker's loudness level), N_{max}, (maximum loudness), N_5, and $L_{m,1/1(63-500\,\text{Hz})}$. They all showed good correlations with annoyance, especially L_{Amax}, L_{Aeq}, LL_Z, N_{max}, and $L_{m,1/1(63-500\,\text{Hz})}$, which were concluded to be good descriptors of subjective annoyance, with reported correlation coefficients higher than 0.88 for all impact ball groups. Zwicker's loudness LL_Z showed the highest correlation $r=0.97$ ($R^2=0.94$, $p<0.05$), L_{Amax} was sufficient with $r=0.92$ ($R^2=0.85$, $p<0.01$), while the lowest coefficient was $r=0.88$ ($R^2=0.77$, $p<0.01$) for $L_{i,Fmax,AW}$. The authors emphasize on the importance of loudness level LL_Z for predicting the annoyance response and L_{Amax} is suggested as the most practical descriptor, due to easy measuring with a sound level meter.

In a second test, 36 stimuli sounds were evaluated by the same participants in pair comparisons to explore the effects of the psychoacoustic metrics as variables: loudness (L), sharpness (S), roughness (R), and fluctuation strength (F) on the annoyance. In a regression analysis, loudness and fluctuation strength were found to be highly correlated with subjective responses, with coefficients $r=0.81$ ($p<0.01$) and $r=0.90$ ($p<0.05$), respectively, in the individual linear models. A multiple regression model for the subjective variable annoyance was chosen, using the best combination of metrics as $SV_{annoyance} = 0.77L + 0.15F$, with a total coefficient $r=0.90$ ($R^2=0.81$, $p<0.05$). Thus, the authors highlight that except the main effect of loudness, temporal variations in low frequencies play a role as well in the annoyance perception.

In addition, a semantic differential test took place for a set of 12 adjective pairs for evaluating floor impact sound after a selection process. The same 40 people participated and used a bipolar scale (with an adjective and its opposite) to characterize the given sound stimuli. Their responses were processed using the method of factor analysis, revealing three dimension groups, entitled by the authors as "1: reverberance and spaciousness," "2: dullness," and "3: loudness." The first dimension was well correlated with roughness ($r=0.69$, $R^2=0.48$, $p<0.05$), the second with fluctuation strength ($r=0.71$, $R^2=0.50$, $p<0.05$), as well as the third ($r=0.73$, $R^2=0.53$, $p<0.01$), which was also associated with loudness with $r = 0.75$ ($R^2 = 0.56$, $p < 0.05$). The authors conclude that several frequency characteristics can be described by those three reported categories.

In Jeon and Sato,[7] the annoyance of floor impact sounds was evaluated using the ACF and SQ metrics. Two impact sources were used, the bang machine and the impact ball for measurements in six apartments with different insulation configurations. Binaural recordings were taken also with a dummy head to create 28 pairs of sound stimuli for a pairwise comparison. The stimuli were classified into three groups according to their spectral behavior. Then, 40 subjects (20 students and 20 housewives) took part in a laboratory listening test; 35 of them distinguished various levels of annoyance ($p < 0.05$) and the agreement among all responses was significant ($p < 0.05$).

Single and multiple regression analyses were performed. Three ACF parameters were selected for a regression model: $SV_{annoyance} \approx 0.61\Phi(0) + 0.15VAR\_\Phi(0) - 0.46VAR\_\varphi_1$. $\Phi(0)$ stands for the maximum amplitude of sound energy, φ_1 is the maximum ACF amplitude, and VAR denotes the variance of the parameters. The correlation coefficients between annoyance responses and the chosen parameters were 0.66 for $\Phi(0)$, 0.13 for $VAR\_\Phi(0)$, and −0.29 for VAR_φ_1. Regarding SQ parameters, loudness (L) and fluctuation strength (FS) correlated best with subjective annoyance and provided r values 0.66 and 0.38, respectively. They were selected for the model $SV_{annoyance} = 0.63L + 0.34FS$, which is different from the model presented before in Hongisto et al.[26] However, the total coefficients for the above models are not reported. Overall, $\Phi(0)$ and loudness were the most correlated from the studied parameters. It is highlighted that the variance of $\Phi(0)$ and φ_1 can play a role in annoyance prediction since they are related to the pitch (tonality) of the noise signal. Floor structures with higher resonance frequencies had lower sound levels from the heavy impact sources. Floors with viscoelastic damping materials had reduced impact sound levels and thus corresponded to lower annoyance ratings. However, structures with resilient isolators (floating floor types) did not offer reduced annoyance in all cases, as it might be expected. Jeon and Sato[7] state that this happens because "isolators amplify low-frequency noises (below 100 Hz) generally produced by heavyweight impacts."

In Jeon et al.,[8] the interaural cross-correlation (IACC) function was used in the evaluation of floor impact annoyance. Impact ball measurements inside Korean apartments and 87 binaural recordings took place: they were used in a laboratory listening test with 20 participants (aged 24–35 years). In the first part, random pairs of stimuli were presented to the subjects who were asked to choose the stronger sound. The JND of the L_{Amax} levels (manipulated SPL) and IACC levels were explored. The JND value was acquired when 75% of the subjects could distinguish between a test sample and the reference with different measures of L_{Amax} and IACC values. Overall, the JND for the SPL was found 1.5 dB differences of L_{Amax} and for the IACC levels between 0.12 and 0.13.

Then, nine of the stimuli were chosen for the second part where the subjects rated relative annoyance in pair comparisons again. The effects of SPL and IACC were found statistically significant in the ANOVA ($p < 0.01$) but not their interactions. Then, a regression model was determined as $SV_{annoyance} \approx -0.34(IACC) + 0.95(SPL)$, with statistically significant individual coefficients ($p < 0.01$) and total correlation coefficient ($r = 0.78$, $p < 0.01$). The annoyance ratings increased as IACC decreased and SPL increased. SPL and IACC contributed to the regression model by 79.3% and 20.4%, respectively. The temporal variations of IACC (T.var_IACC) were explored as well in association with subjective annoyance; the subjects offered consistently and significantly ($p < 0.05$) agreed that SPL and T.var_IACC contribute independently to annoyance at 94.2% and 2.7%, respectively ($p < 0.01$). Also, it was concluded that for the floor structures with damping materials, the IACC values are greater than floors with resilient isolator: there is better energy absorption and less sidewall transmission with damping layers in floors.

A continuation study of Jeon et al.[8] is presented in Kim et al.[9] that deals with the temporal decay of impact sounds and how that affects subjective perception. For that investigation, the JND of decay rate (DR) was used for impact ball sound samples. The test samples were created after processing of 92 field recordings in apartments of concrete box-framed buildings; they were classified in three spectrum groups according to Jeon and Sato.[7] In addition, the authors mention that the effects of floor and room conditions on the recordings were investigated with ANOVA and found statistically significant, specifically factors such as floor thickness, area, room volume, and type. However, no details are provided for those variables. The metric DR is similar to reverberation time (RT) and corresponds to the decay of a signal (normalized to 0 dB): for example, from −5 to −35 dB for DR30. The subjects rated the sounds using pairwise comparisons in a laboratory listening test. If more than 75% of the subjects distinguish the reference sound and the test sample, JND is valid according to this study.

In the first test, 15 test sound stimuli were judged by the participants if they sound similar; the JND was determined when the DR difference of the stimuli was 11 dB/s between test sounds and reference. That means the subjects started to decide that the tested stimuli were different sounds when their actual difference in DR was more than 11 dB/s (slope of 11 dB drop per second). In the second test, the participants offered annoyance ratings of nine test sounds. It was found that the annoyance values increase when both L_{AE} (SPL) and DR increase. Also, longer decays (DR) cause higher annoyance when L_{AE} is constant; when DR is constant, then louder stimuli cause higher annoyance. ANOVA results indicated that the interactions of the factors SPL, DR, and spectrum group were not statistically significant. A multiple regression model was developed as $SV_{annoyance} = -0.02DR + 0.18SPL - 8.21$ with reported total coefficient $R = 0.84$ ($R^2 = 0.71, p < 0.01$). The contribution of the modeling factors was 23% for DR and 76% for SPL. Therefore, a correction for the A-weighted maximum level $L_{A,Fmax}$ rating index is proposed considering the effect for DR as $L_{i,Fmax,c} = L_{i,Fmax} - a(DR_i / DR_{mean})$. When the latter correction was applied, the linear regression results were drastically improved: the subjective annoyance was associated with $L_{A,Fmax}$ with $R^2 = 0.98$ instead of $R^2 = 0.65$ (without correction).

In another continuation study,[10] the classification of annoyance and acceptability of SPL and temporal decay levels (DR) was explored. Similar sound stimuli as in Jeon et al.[8] were used and 30 subjects in a listening test rated their annoyance in a 7-point-scale and acceptability (yes/no). Both DR30 and DR60 were tested for decays of 30 and 60 dB, respectively. No significant differences were reported between DR30 and DR60 below impact level differences of $L_{Amax} = 61\,\text{dB A}$, but significant differences were found above $L_{Amax} = 67\,\text{dB A}$ ($p < 0.01$). Sounds evaluated with DR30 were rated as more annoying than DR60, indicating that above a DR slope of 60dB A/s, there is a significant effect of temporal decay on annoyance. Dose-response curves for the percentage of annoyed subjects relevant to SPL (L_{Amax}) and DR30 and DR60 are presented, but no statistical details given. A classification system for annoyance from impact sound was developed with four classes based on the percentage of annoyed subjects (%A who rated “3—Moderately” and higher). Class A includes the upper quantile 0%A–25%A of annoyed subjects (criteria in L_{Amax} for cases of DRs: DR30 < 44.5 dB A or DR60 < 45.4 dB A), and then, other classes were defined as Class B (25%A–50%A, DR30 < 49.2 dB A or DR60 < 50 dB A), Class C (50%A–75%A, DR30 < 53.8 dB A or DR60 < 54.5 dB A), and Class D (75%A–100%A, DR30 > 53.8 dB A or DR60 > 54.5 dB A). A similar classification system is proposed for the percentage of highly annoyed subjects (%HA who rated “4—Considerably” and higher). The acceptable limit for impact sound in terms of L_{Amax} was found at circa 50 dB A, which corresponds Class to A and B (%A) from the developed system, thus the authors consider it as reliable.

In Ryu et al.,[11] a study for the relation between subjective annoyance and single number quantities (SNQs) for impact sounds in wooden buildings in Japan is reported. Excitation by bang machine and impact ball was used for measurements and mono-aural recordings on 26 floors of 12 real buildings; 2 typical spectra were defined for the study, SP-1 and SP-2 to be used as reference, and another

11 stimuli for each typical spectrum were created with manipulation of the frequency responses. In all, 17 subjects (aged circa 20 years) took part in a listening experiment where they rated the 24 sound stimuli in a pair comparison test (55 pairs) using a relative annoyance scale from −3 to 3 (0 for equal annoyance between stimuli). The various impact sound levels (with different types of weighting) were defined in the Japanese standard: $L_{i,Fmax,r}$, $L_{i,Fmax,AW}$, $L_{i,Fmax}$, and $L_{i,Favg,Fmax}$ were assessed for the sound stimuli. Loudness (N_5) was used too. They were all very well correlated to annoyance with r values ranging from 0.89 to 0.99: the best correlations were equal to 0.99 for N_5 and 0.96 for $L_{i,Favg,Fmax}$ in both cases of SP-1 and SP-2. All responses were found to be significantly different (p < 0.01).

A second experiment took part in the same study with 31 subjects (aged circa 20 years) where impact sounds dependent on the SPL were compared to a reference sound (SP-2). Two separate levels of 55 and 65 dB in $L_{i,Fmax,r}$ (denoted L55 and L65) were used for the compared stimuli in pair comparisons using the same methodology as before. The associations between SNQs and relative annoyance differed a lot; correlation coefficients varied from 0.39 to 0.93, while bigger associations with annoyance were found for the L55 stimuli. Most results were statistically significant (p < 0.01) especially for the L65; r values ranging from 0.81 for $L_{i,Favg,Fmax}$ to 0.91 for N_5, while the same values for L55 stimuli were from 0.84 for $L_{i,Favg,Fmax}$ to 0.74 for N_5. It is concluded that arithmetic averages of octave-band SPL like $L_{i,Favg,Fmax}$ and Zwicker's loudness percentile N_5 describe well the subjective annoyance and can be used as sufficient SNQ, but N_5 is characterized difficult to calculate, as also in Lee et al.[6]

A wide research study took place in the National Research Council of Canada in Ottawa,[12,13] specifically for the ranking of lightweight (LW) wood framed floor-ceiling structures based on the subjective response of participants. First, a wide set of 19 various bare floor assemblies was measured in laboratory conditions (two vertically adjacent reverberation rooms with a specimen opening). All standardized excitation sources were used; the standardized tapping machine, the modified tapping machine (i.e. the standardized one on a resilient layer), the heavy/soft rubber ball dropped from the heights of 10, 50, and 100 cm, and additionally the tire machine was used as well. Sound recordings were taken for the rubber ball cases and additionally with a human source: an adult walking barefoot on the test floors. A total of 90 samples were used in a pairwise comparison test; 12 participants took part in the laboratory test and rated the sounds in a relative annoyance scale from 1 to 9 (1—'Sound 2 much less annoying,' 5—'equally annoying sounds,' and 9—'Sound 2 much more annoying'). Sound 1 was always the same reference and Sound 2 was the tested sample.

A correlation analysis was performed to investigate the relationship between the subjective annoyance and the acoustic data collected in the measurements. The highest association was reported between the annoyance levels and the metrics derived with the standard tapping machine; $L_{n,w}$, $L_{n,w} + C_{I,50-2500}$, and $L_{n,w} + C_{I,100-2500}$. The determination coefficients R^2 were equal to 0.85, 0.87, and 0.83, respectively, for the walking sounds case and 0.89, 0.90, and 0.96, respectively, for rubber ball impact noise. The relevant results for the measurements with the hard/soft impact ball (according to JIS A 1418 and KS F 2863) and the metrics $L_{i,Fmax,r}$, $L_{i,Fmax,AW}$, and $L_{i,Fmax(63-1\text{kHz})}$ were also satisfactory with R^2 values 0.70, 0.80, and 0.80, respectively, for walking and 0.86, 0.93, and 0.93, respectively, for rubber ball annoyance. The tire machine outcome was the worst, while the modified tapping machine outcome was sufficiently associated with R^2 values ranging from 0.71 to 0.84. Summing up, according to this study, the use of the standard tapping machine is adequate for predicting the subjective annoyance, without using any other sources. The use of rubber ball is also a good choice since it has shown correlations with subjective annoyance. However, that conclusions were derived using a small group of 12 participants only for the test.

In Späh et al.,[14] the European research program AcuWood is presented, which concerns impact noise annoyance in wooden buildings. Measurements of timber floor structures and binaural recordings took place in real buildings and in laboratories following the same methods. Different coverings on the floors were tested during laboratory measurements too. Several impact sources were explored: the standardized tapping machine and the modified one (according to ISO 10140-5), the Japanese impact ball, and "real" impact sources (male walkers with socks and shoes and a female walker with hard heeled shoes and a chair which was drawn). Two separate listening tests took place using the stimuli created from all floors, while a field measurement was common in both tests as a reference. The tests involved 18 and 22 subjects, which provided ratings of annoyance (scale 0–10) according to ISO 15666.[27]

The results indicate that the typically used $L'_{nT,w}$ (range = 100–3150 Hz) was poorly associated with the annoyance due to walking ($r=0.62$, $R^2=0.38$) but with using the lower frequency range and the adaptation term, the result becomes better for $L'_{nT,w}+C_{I,50-2500}$ ($r=0.76$, $R^2=0.58$). Different rating curves proposed for evaluation of the ISO 717-2[20] method for assessment of impact noise levels with the tapping machine were tested; the best associations between walking noise annoyance and impact noise descriptors were found for $L'_{n,w}+C_{I,50-2500}$ ($r=0.78$, $R^2=0.61$), $L'_{nT,\,Hagberg03}$ ($r=0.79$, $R^2=0.63$), $L'_{nT,\,Hagberg04}$ ($r=0.79$, $R^2=0.62$) and $L'_{nT,\,Bodlund}$ ($r=0.77$, $R^2=0.58$). The last three descriptors are variations of $L'_{n,w}+C_I$, with correction spectra C_I differentiated from the standardized ones: they were acquired from past field research and tested again in the laboratory.[14] For the moving chair annoyance, the best associations with the descriptors for tapping machine measurements were found for $L'_{nT,w}+C_{I,50-2500}$ ($r=0.85$, $R^2=0.72$) and $L'_{nT,\,Bodlund}$ ($r=0.85$, $R^2=0.73$). The modified machine descriptors offered better results for $L'_{n,\,TA\,20-2500}$ ($r=0.91$, $R^2=0.82$) and the best for $L'_{n,\,TA\,50-2500}$ ($r=0.92$, $R^2=0.84$). The impact ball descriptor relates very well to moving chair annoyance: $L'_{nT,w}+C_{I,50-2500}$ ($r=0.91$, $R^2=0.82$) as well. It is concluded that the Japanese impact ball is the most appropriate source to represent walking noise annoyance due to frequency spectrum similarities; the modified tapping machine offered slightly better associations but it is considered impractical. The need of measuring down to 50 Hz to acquire good associations with subjective annoyance is highlighted.

Another study in Finland took place[15,16] exploring the associations of descriptors derived from impact sound on concrete floors and subjective annoyance; the relation of eight impact noise descriptors to subjective ratings was studied. A listening test was conducted with 55 subjects (25 males and 30 females, age 25–57 years, mean 27 years) who offered their ratings on a set of five recorded impact sounds through nine floor configurations in a psychoacoustic listening experiment at the Finish Institute of Occupational Health. A floor construction was measured in a laboratory, being bare concrete or with eight different floor covering types, according to ISO 140-7. The eight SNQs explored were $L'_{n,w}$, $L'_{n,w}+C_I$, $L'_{n,w}+C_{I,50-2500}$ (according to ISO 717-2[22]), $L'_{n,w,Fas}$, $L'_{n,w,Fas,\,50}$, $L'_{n,w,Ger}$, $L'_{n,w,Bod}$, and $L'_{n,w,Hag}$. The last five descriptors are variations of $L'_{n,w}+C_I$, with correction spectra C_I differentiated from the standardized ones: they were acquired from past field research and tested again in the laboratory.[15,16] The recorded sound types were walking with hard shoes, socks and soft shoes, a bouncing ball, and a moving chair. The participants were asked to rate the sound samples in terms of perceived loudness and annoyance in a scale of 0–10 (0—'Not audible,' 1—'Not at all …' and 10—'Extremely …') and also in terms of acceptability in a scale of 0–3.

For three sound types S1, S3, and S5 (walking with hard shoes, soft shoes, and moving chair), the correlations were considered sufficient and statistically significant ($p<0.01$) for most SNQs, with determination coefficient R^2 values ranging from 0.25 to 0.60. Overall, $L'_{n,w}+C_{I,50-2500}$ is proposed as the most suitable indicator for S1, S3, and S5 having good associations with both loudness (reported R^2 values 0.56, 0.37, and 0.53, respectively) and annoyance (R^2 values 0.49, 0.31, and 0.47, respectively). This is in agreement with the results presented in Rychtáriková et al.[20] The other standardized descriptor $L'_{n,w}+C_I$ is considered good for perceived loudness prediction as well with reported R^2 values 0.57, 0.39, and 0.50, respectively, for S, S3, and S5.

For the other sound types (S2: walking with socks and S4: bouncing ball), the associations were weak with R^2 ranging from 0.03 to 0.16. The metrics $L'_{n,w}+C_I$, $L'_{n,w}+C_{I,50-2500}$, $L'_{n,w,Fas}$, $L'_{n,w,Fas,50}$, $L'_{n,w,Ger}$, and $L'_{n,w,Bod}$ were found to be the best indicators for both subjective loudness and annoyance. For the acceptability, it is only reported that the determination coefficients are similar to the ones acquired for the loudness and annoyance perception cases. It is concluded that inclusion of low frequencies 50–100 Hz in the SNQs offers better correlation between a SNQ and the subjective responses. They summarize also that more SNQs should be developed to represent all types of typical impact noise sounds in buildings and their spectra.

In Öqvist et al.,[17] a study is presented where the authors investigate the effect of the frequency range 20–50 Hz in the perception of walking sound annoyance. A listening experiment with 24 Swedish subjects (12 males and 12 females, age mean 27 years, standard deviation (SD) = 5 years) took place, where walking sound samples were evaluated. The latter concerned recordings of a male walker with socks or shoes through two construction cases: a wooden LW and a concrete heavyweight (HW). They were tested in a pairwise comparison test which showed that the percentage of subjects perceiving a difference in annoyance was significantly higher for the LW floor case; 20 Hz was indicated as the limit for perceived annoyance and as an important limit to evaluate walking with socks. It is highlighted that existing impact sound SNQs are not sufficient in terms of correlation to subjective responses. It was confirmed that frequencies down to 20 Hz are necessary to evaluate impact sounds in LW, while 40 Hz was the lowest limit for walking with socks in HW and 100 Hz for shoes in HW. In addition, the highest correlation between annoyance responses and standardized descriptors is reported for $L'_{nT,w}+C_{I,20-2500}$ and $L'_{nT,w}+C_{I,25-2500}$, so they are considered the optimized SNQs in this study. This is in agreement with the previous findings as in Gover et al.[12,13] However, statistical details for correlation and significance are not reported.

Discussion

In the presented studies, various descriptors have been used to associate to self-reported responses, mostly for annoyance or loudness. However, the lack of a proper SNQ that could work efficiently for all types of impact noise is apparent or directly concluded in many studies.[14–16]

The inclusion of low frequencies (down to 50 Hz) seems to be an important concern. Many of the reviewed studies indicate that extended frequency spectra which include low frequencies down to 50 Hz correlate better with subjective responses of annoyance.[14–17] Variations exist as well regarding several types of impact sources tested in different studies, but the overall associations of subjective responses to impact sound are sufficiently good and become better with extended spectra. That is a general issue discussed in the field of building acoustics.[1,14]

The indicators for the standardized tapping machine seem to predict well the overall subjective noise annoyance in many studies,[4,5,12–16] but do not associate well enough with walking noise.[12,13] The Japanese impact ball seems to represent better impact sounds induced by human walking as demonstrated in many Korean and Japanese studies;[5–11] it is summarized that impact ball as an impact source corresponds better to the usual impact noise spectra found in residential multistory buildings, especially human walking and kids jumping. It is also noticeable that Korean researchers differentiate between HW (impact ball and bang machine) and LW impact sounds (tapping machine) in their publications.

In some studies, both loudness and annoyance ratings were included for the self-reported assessment of the participants,[4,16] and loudness scale only was used in one study.[5] Some similar results have been between loudness and annoyance ratings,[16] but overall no final conclusion has been done on the differences and similarities for the case of impact sound perception related to loudness or annoyance.

In some studies, SQ metrics are examined for the subjective annoyance assessment.[3,5–7] In Lee et al.,[6] the authors highlight the significance of Zwicker loudness level, LL_Z , for predicting annoyance response. Some of the studies focus on the effects of ACF and IACC. Few studies focus on the effect of SQ metrics only[2] or their combination to ACF/IACC.[3,7] Some studies explore specifically the effect of temporal decay with DR.[9,10] In overall, they all conclude that temporal characteristics are important for the prediction of self-reported annoyance in literatures.[2,3,7–10] In many cases, the parameter of maximum amplitude Φ (0) was highlighted as significant.[2,3,6] Furthermore, additional properties of sound signals such as modulation and fluctuation were mentioned as important.[3,7,8]

Many multiple regression models have been presented for the prediction of self-reported annoyance.[3,6,7] The most successful regression models are presented in Yeon and Jeong,[3] and they both have total correlation coefficient $r=0.98$ ($p<0.05$) and concern annoyance prediction based on acoustic measurements from the following:

Tapping machine data: $SV_{tapping}=-5.731+0.25\,L+2.23\,FS+1.16\,T-0.0076\,UA$.

Impact ball: $SV_{Ball}=-4.754+0.121\,\Phi(0)-0.2021\,\tau_e-1.01\,IACC+0.992\,\tau_{IACC}$.

The variability of impact noise sensitivity due to different culture is featured in only one study,[4] where subjects from Germany and Korea took part in the presented experiment. A big difference was revealed; therefore, intercultural responses to impact noise might be an interesting issue for further studies.

Classification took place in two studies only. In Jeon et al.,[5] 98 subjects evaluated impact ball noise and the following three categories were proposed using an annoyance scale from 1 to 9: “Audibility” (1–3), “Disturbance” (4–6), and “Amenity” (7–9). In addition, in Jeon and Oh,[10] four classes were developed based on self-reported annoyance percentages (Class A–B, %A), and minimum SPL levels of the DR for every class were defined.

Most of the studies have a good level of presentation and evaluation of research evidence as can be seen in Table 2. Many statistical evaluations took place; some were incomplete with missing important parameters or some details were not reported at all.[2,7] In some listening tests, very small amounts of subject have participated.[11–13] This fact weakens the strength of association, the consistency, the biological gradient, and the analogy of the acquired results, as demonstrated also in Table 2.

Conclusion

This review shows that annoyance perception due to impact sound is an important issue and can be associated well in overall to acoustic measurements. Many standardized SNQs and alternative descriptors have been evaluated and associate well with subjective responses collected in laboratory listening tests. The standardized descriptors based on the tapping machine measurements are considered sufficient, but the highest correlations have been found between SQ metrics and subjective ratings. Inclusion of low frequencies down to 50 Hz in measurements helps impact sound descriptors to relate better to subjective responses. Furthermore, all descriptors do not relate well to all kinds of impact sound related. The impact sources suggested as efficient are the standardized tapping machine for overall annoyance, the Japanese impact ball for human walking annoyance, or typical impact sounds in dwellings. Additional properties of noise signal such as modulation, decay, and other temporal characteristics evaluated by the ACF, the IACC, the DR, or SQ metrics are indicated to play an important role in annoyance rating and perception.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support of the research, authorship, and/or publication of this article: This article was written within the research project “Acoustic Comfort in Building Apartments” funded by Saint-Gobain Weber.

References

1. Rasmussen B and Rindel JH. Concepts for evaluation of sound insulation of dwellings—from chaos to consensus? In: *Proceedings of the Forum Acusticum 2005*, Budapest, 2005, http://orbit.dtu.dk/files/2460104/oersted-dtu1603.pdf
2. Yeon JY. Subjective evaluation of floor impact noise based on the model of ACF/IACF. *J Sound Vib* 2001; 241(1): 147–155.
3. Yeon JY and Jeong JH. Objective and subjective evaluation of floor impact noise. *J Temp Des Architect Environ* 2002; 2(1): 20–28.
4. Jeon JY, Jeong JH, Vorländer M, et al. Evaluation of floor impact sound insulation in reinforced concrete buildings. *Acta Acust United Ac* 2004; 90: 313–318.
5. Jeon JY, Ryu JK, Jeong JH, et al. Review of impact ball in evaluating floor impact sound. *Acta Acust United Ac* 2006; 92: 777–786.
6. Lee PJ, Kim JH and Jeon JY. Psychoacoustical characteristics of impact ball sounds on concrete floors. *Acta Acust United Ac* 2009; 95: 707–717.
7. Jeon JY and Sato S. Annoyance caused by heavyweight floor impact sounds in relation to the autocorrelation function and sound quality metrics. *J Sound Vib* 2008; 311: 767–785.
8. Jeon JY, Lee PJ, Kim JH, et al. Subjective evaluation of heavy-weight floor impact sounds in relation to spatial characteristics. *J Acoust Soc Am* 2009; 125(5): 2987–2994.
9. Kim JH, Ryu JK and Jeon JY. Effect of temporal decay on perception of heavy-weight floor impact sounds. *J Acoust Soc Am* 2013; 134(4): 2730–2738.
10. Jeon JY and Oh SM. Psychoacoustical evaluation of heavyweight floor impact sounds in apartment buildings. In: *Proceedings of the inter-noise 2014*, Melbourne, VIC, Australia, 16–19 November 2014.
11. Ryu J, Sato H, Kurakata K, et al. Relation between annoyance and single-number quantities for rating heavy-weight floor impact sound insulation in wooden houses. *J Acoust Soc Am* 2011; 129(5): 3047–3055.
12. Gover BN, Bradley J, Schoenwald S, et al. Subjective ranking of footstep and low-frequency impact sounds on lightweight wood-framed floor assemblies. In: *Proceedings of the Forum Acusticum 2011*, Aalborg, 26 June 2011.
13. Gover BN, Bradley JS, Zeitler B, et al. 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 2011*, Osaka, Japan, 4 September 2011.
14. Späh M, Hagberg K, Bartlomé O, et al. Subjective and objective evaluation of impact noise sources in wooden buildings. *Build Acoust* 2013; 20(3): 193–214.
15. Kylliäinen M, Hongisto V, Oliva D, et al. A laboratory listening experiment on subjective and objective rating of impact sound insulation of concrete floors. In: *Proceedings of the inter-noise 2016*, Hamburg, 21–24 August 2016.
16. Kylliäinen M, Hongisto V, Oliva D, et al. Subjective and objective rating of impact sound insulation of a concrete floor with various coverings. *Acta Acust United Ac* 2017; 103: 236–250.
17. Öqvist R, Ljunggren F and Johnsson R. Listening test of walking noise from 20 Hz in dwellings. In: *Proceedings of the inter-noise 2017*, Hong Kong, China, 7 December 2017, pp. 3935–3942. Reston, VA: Institute of Noise Control Engineering.
18. Monteiro C, Machimbarrena M, De la Prida D, et al. Subjective and objective acoustic performance ranking of heavy and light weight walls. *Appl Acoust* 2016; 110: 268–279.
19. Rychtáriková M, Muellner H, Chmelík V, et al. Perceived loudness of neighbour sounds heard through heavy and light-weight walls with equal R_w+ C_(50–5000). *Acta Acust United Ac* 2016; 102(1): 58–66.

20. Rychtáriková M, Roozen B, Müllner H, et al. Listening test experiments for comparisons of sound transmitted through light weight and heavy weight walls. *Akustika* 2013; 19: 8–13.
21. Rychtáriková M, Müllner H, Urbán D, et al. Influence of temporal and spectral features of neighbour's noise on perception of its loudness. In: *Proceedings of the inner-noise 2013*, Innsbruck, 15–18 September 2012.
22. Pedersen TH, Antunes S and Rasmussen B. Online listening tests on sound insulation of walls—a feasibility study. In: *Proceedings of the inner-noise 2012*, Prague, 2012, http://vbn.aau.dk/files/69825530/EuroNoise2012_Pedersen_Antunes_Rasmussen_OnlineListeningTests_Feasibility.pdf
23. Park HK, Bradley JS and Gover BN. Evaluating airborne sound insulation in terms of speech intelligibility. *J Acoust Soc Am* 2008; 123(3): 1458–1471.
24. Park HK, Bradley JS and Gover BN. Evaluation of airborne sound insulation in terms of speech intelligibility, Research Report (National Research Council Canada. Institute for Research in Construction); no. RR-228, NRC Institute for Research in Construction. National Research Council Canada: Canada, 2007.
25. Park HK and Bradley JS. Evaluating standard airborne sound insulation measures in terms of annoyance, loudness and audibility ratings. *J Acoust Soc Am* 2009; 126(1): 208–219.
26. Hongisto V, Oliva D and Keränen J. Subjective and objective rating of airborne sound insulation—living sounds. *Acta Acust United Ac* 2014; 100: 848–864.
27. Virjonen P, Hongisto V and Oliva D. Optimized single-number quantity for rating the airborne sound insulation of constructions: living sounds. *J Acoust Soc Am* 2016; 140(6): 4428–4436.
28. Ljunggren F, Simmons C and Hagberg K. Correlation between sound insulation and occupants' perception—proposal of alternative single number rating of impact sound. *Appl Acoust* 2014; 85: 57–68.
29. Ljunggren F, Simmons C and Hagberg K. Findings from the AkuLite project: correlation between measured vibro-acoustic parameters and subjective perception in lightweight buildings. In: *Proceedings of the inter-noise 2013*, Innsbruck, 15–18 September 2013.
30. Simmons C and Ljunggren F. Aku20—searching for optimal single number quantities in EN ISO 717-2 correlating field measurements 20-5000Hz to occupant's ratings of impact sounds—new findings for concrete floors. In: *Proceedings of the Euronoise 2015*, Maastricht, 31 May–3 June 2015.
31. Ljunggren F, Simmons C and Öqvist R. Correlation between sound insulation and occupants' perception—proposal of alternative single number rating of impact sound-part II. *Appl Acoust* 2017; 123: 143–151.
32. Ljunggren F, Simmons C and Öqvist R. Evaluation of impact sound insulation from 20Hz. In: *Proceedings of the 24th international congress on sound and vibration, ICSV24*, London, 23–24 July 2017.
33. Guigou-Carter C, Balanant N and Villenave M. Acoustic comfort evaluation in lightweight wood-based buildings. In: *Proceedings of the Forum Acusticum*, Krakow, 7–12 September 2014.
34. Milford I, Høsøien CO, Løvstad A, et al. Socio-acoustic survey of sound quality in dwellings in Norway. In: *Proceedings of the inter-noise 2016*, Hamburg, 21 August 2016.
35. Høsøien CO, Rindel JH, Løvstad A, et al. Impact sound insulation and perceived sound quality. In: *Proceedings of the inter-noise 2016*, Hamburg, 21 August 2016.
36. Hagberg K. Evaluating field measurements of impact sound. *J Build Acoust* 2010; 17: 105–128.
37. Hongisto V, Mäkilä M and Suokas M. Satisfaction with sound insulation in residential dwellings—the effect of wall construction. *J Build Environ* 2015; 86: 309–320.
38. ISO 532:1975. Acoustics—method for calculating loudness level.
39. Zwicker E and Fastl H. *Psycho-acoustics: facts and models*. Berlin: Springer-Verlag, 1990.
40. KS F 2810-2:2001. Method for field measurement of floor impact sound insulation —part 2: method using standardized heavy impact sources.
41. ISO 717-2:1996. Acoustics—rating of sound insulation in buildings and of buildings elements—part 2: impact sound insulation.
42. JIS A 1418-2:2000. Acoustic—measurement of floor impact sound insulation of buildings—part 2: method using standard heavy impact sources.

43. ISO 140-7:1998. Acoustics—measurement of sound insulation in buildings and of building elements—part 7: field measurements of impact sound insulation of building elements.
44. EN ISO 12354-2:2017. Building acoustics—estimation of acoustic performance of buildings from the performance of elements—part 2: impact sound insulation between rooms.
45. ISO 16283-2:2014. Field measurement of sound insulation in buildings and of building elements—part 2: impact sound insulation.

Paper C

Soundscapes of Buildings and Built Environments

BUILDING ACOUSTICS

Building Acoustics
2018, Vol. 25(4) 289–305

Article reuse guidelines:
sagepub.com/journals-permissions
DOI: 10.1177/1351010X18788685
journals.sagepub.com/home/bua
SAGE

Review of acoustic comfort evaluation in dwellings: Part III—airborne sound data associated with subjective responses in laboratory tests

Nikolaos-Georgios Vardaxis and Delphine Bard

Abstract

Acoustic comfort has been used in engineering to refer to conditions of low noise levels or annoyance, while current standardized methods for airborne and impact sound reduction are used to assess acoustic comfort in dwellings. However, the results and descriptors acquired from acoustic measurements do not represent the human perception of sound or comfort levels. This article is a review of laboratory studies concerning airborne sound in dwellings. Specifically, this review presents studies that approach acoustic comfort via the association of objective and subjective data in laboratory listening tests, combining airborne sound acoustic data, and subjective ratings. The presented studies are tabulated and evaluated using Bradford Hill's criteria. Many of them attempt to predict subjective noise annoyance and find the best single number quantity for that reason. The results indicate that subjective response to airborne sound is complicated and varies according to different sound stimuli. It can be associated sufficiently with airborne sound in general but different descriptors relate best to music sounds or speech stimuli. The inclusion of low frequencies down to 50 Hz in the measurements seems to weaken the association of self-reported responses to airborne sound types except for the cases of music stimuli.

Keywords

Acoustic comfort, airborne sound, laboratory, subjective responses, association, evaluation

Introduction

This is the third and final part of a review of acoustic comfort evaluation in dwellings. It is accompanying part I, which reviewed subjective responses to field data from building surveys[1] and part

Division of Engineering Acoustics, Department of Construction Sciences, Faculty of Engineering LTH, Lund University, Lund, Sweden

Corresponding author:
Nikolaos-Georgios Vardaxis, Division of Engineering Acoustics, Department of Construction Sciences, Faculty of Engineering LTH, Lund University, Lund 221 00, Sweden.
Email: nikolas.vardaxis@construction.lth.se

II, which reviewed subjective responses to impact sound data in laboratory tests.[2] This article is focused on subjective responses relevant to airborne sound data used in laboratory tests.

The presented studies of this review approach acoustic comfort through the association of acoustic data and subjective responses: they analyze laboratory listening tests that utilize airborne sound reduction data from measurements and sometimes involve recorded sounds of various noise types. The acoustic data are utilized in controlled listening experiments where the subjects (participants) provide their self-reported responses.[3–13] In some cases, the acoustic data come from in situ measurements or sound recordings in test buildings. However, the data are still processed and used for listening experiments within a laboratory setup under controlled conditions in some reviewed studies.

The laboratory studies of airborne sound concern mainly the perception of annoyance or loudness of noise within living environments, the evaluation of existing standardized indicators, and the rating of building elements. Fewer studies were found concerning airborne sound reduction than the ones concerning impact sound. That is mainly because impact sound types have been reported as the most disturbing in residential environments.[14]

The concept of acoustic comfort is hardly defined in the literature, despite being an important concept in engineering. It is typically used to consider a state of low or no noise and therefore lack of annoyance for the residents. A complete definition is provided in Rasmussen and Rindel,[14] as: "a concept that can be characterized by absence of unwanted sound, desired sounds with the right level and quality, opportunities for acoustic activities without annoying other people."

Standardized measurements and indicators are used to assess acoustic conditions in buildings;[14] they are also used as a measure of acoustic comfort. But they do not always represent the perception of people in living sound environments. For instance, there are different types of building components, such as walls that offer various insulation and acoustic conditions in residencies.[3–6] In some other cases the characteristics of noise types might influence in various ways the perception of subjects: thus different standardized descriptors work better for various sound sources.[10–13]

Therefore, the relation of the measured acoustic data to self-reported responses is important to study. The level of association is explored with statistical analyses comparing objective and subjective data. If a strong association is found between a descriptor and the subjective responses, then that descriptor could be used to predict the response of residents to a living environment based on acoustic data. Alternative versions of standardized descriptors with new adaptation terms are introduced many times in order to achieve stronger association of acoustic data with subjective responses.[10–13] Consequently, the study of acoustic comfort and the development of prediction models constitute an essential tool for building design with proper acoustic conditions.

Methods

A wide search for peer-reviewed publications and conference proceedings, which include examination between acoustic data and subjective responses relevant to airborne sound, has been done in the following databases: ScienceDirect, AIP Scitation, Ingenta Connect, ResearchGate, PubMed, Scopus, and Google Scholar. The search method included numerous searches in the databases using relevant keywords, such as objective, subjective, acoustic, psychoacoustic, self-report, rating, score, comfort, quality, airborne, sound, insulation, noise, annoyance, assessment, association, correlation. Several publications were subsequently found as references of the first selected papers.

This review article includes 11 studies: eight European studies,[3–8,12,13] one Asian study,[9] and two Canadian studies.[10,11] In overall, 37 papers were found during the search in databases or relevant references and were evaluated by title name, abstract reading, and full reading. Only 11 papers met the requirements of this review: they offered comparison of results between airborne sound data and subjective responses, which is the subject of focus in this review. The other papers found were excluded because they concerned impact sound laboratory studies[15–30] or field studies.[31–40] Other exclusion criteria were the year of publication and language: only articles published after 1980 in English were included. The bibliographic research took place between April 2015 and September 2017.

Summary of methods, metrics and quantities in the reviewed studies

Many different indicators (or descriptors) are used to represent different quantities in acoustic measurements. They are all standardized in international ISO standards or other compliable national standards. Many variations of them exist as well, since experimental research has been done to acquire better indicators than the standardized ones. A description of all indicators involved in this review is presented in Table 1. For the detailed methods to acquire and calculate the indicators, please see the relevant standards.[41–48]

Several statistical methods are also applied such as analysis of variance (ANOVA) and regression analysis which associate airborne sound data to subjective responses. The quality of statistical association is usually described with typical parameters such as the correlation coefficient, denoted as r, ρ , or R, the coefficient of determination, denoted as R^2. The *p*-values and the confidence intervals (CIs) are measures of statistical significance. Details on the statistical methods can be found in relevant literature.[53]

Some acronyms are used in this manuscript as abbreviations, namely SPL for sound pressure level, SNQ for single number quantity, SRI for sound reduction index (measured frequency spectra), STC for sound transmission class, and TL for transmission loss. The latter two terms are defined in the US standards:[52] they are similar to the airborne SRI R_w .

Evaluation of included studies

The quality of evidence for studies in this review was evaluated by means of Bradford Hill's criteria[54,55] which is an evidence classification method often used in epidemiology and health review studies. The fulfillment of the criteria is rated in this review in a scale of high (+++), moderate (++), low (+), as happened in the previous parts.[1,2] The results are tabulated in Table 3 while the Bradford Hill's criteria are as follows:

Strength of association. It refers to the causality proven by the association between the studied variables (cause, effect size, confounding factors).

Consistency. It indicates the degree of certainty when similar results are observed by different studies in different tests.

Specificity. Specific factors and effects on a specific population lead to a more likely causal relationship.

Temporality. It is based on temporal relations between effects, and used as an indicator for causality, meaning one effect happening after an exposure.

Biological gradient. It refers to the relation between exposure and effect; usually bigger exposure leads to greater effect, but not always, while the opposite outcome can happen as well.

Plausibility. It means that a biological explanation of why a cause leads to a certain effect supports a reasonable causality.

Table 1. Acoustic indicators used in the review studies.

Indicator	Description	Standards	References
R_w	Airborne weighted sound reduction index characterizing a building element (laboratory measurements)	ISO 717-1, ISO 140-3, ISO 16283-1, EN 12354-1	3,4,6,8–11,41–44
R'_w	Apparent airborne sound reduction index (same as R_w, for in situ measurements)	ISO 717-1, ISO 140-4, ISO 10140-2, EN 12354-1	7,41,43,45,46
R_{living}	Airborne weighted sound reduction index used in certain studies, calculated as $R_w + C_{50-5000}$	Similar to R_w	3,4,6,41–43
$R_{A(50-5000)}$	Airborne A-weighted sound reduction index used in certain studies with freq. range 50–5000 Hz	Similar to R_w	5,41–43
R_{speech}	Modified version of $R_w + C_{opt}$	Similar to R_w	12
L_{Aeq}	Sound pressure level equivalent to the total A-weighted levels measured over a stated period of time.	ISO 1996-1:2016	7,9,47
$\bar{L}_{63-4000}$	Arithmetic mean value of sound pressure levels in octave bands of 63–4000 Hz		9
$\bar{L}_{125-4000}$	Arithmetic mean value of sound pressure levels in octave bands of 125–4000 Hz		9
LL	Loudness level		48
PL	Perceived level		49
NC	Noise criteria		50
PNC	Preferred noise criteria		51
STC	Airborne sound transmission class, calculated similar to R_w	ASTM E413	10–12,52
STC_{no8}	Modification of the airborne sound transmission class, ignoring the 8 dB rule (maximum allowed deviation from the rating contour)		10,11
$TL_{200-2500}$	Transmission loss, calculated similar to R_w, with freq. range 200–2500 Hz	ASTM E413	10,52
C	C is an A-weighted pink noise spectrum adaptation term	ISO 717-1, EN ISO 12354-1,	3,4,6,10–13,41–43
$C_{50-3150}$	C adaptation terms, freq. range 50–3150 Hz	Same as C	10,41,42
$C_{50-5000}$	C adaptation terms, freq. range 50–5000 Hz	Same as C	3,4,6,41,42
C_{tr}	C_{tr} is similar to C but represents urban traffic noise spectra; it can be added to $D_{nT,w}$ or R_w to include low-frequency noise influence	Same as C	10–12,41,42
$C_{tr,100-3150}$	$\mathbf{C_{tr}}$ adaptation terms, freq. range 100–3150 Hz	Same as C	10,11
$C_{tr,200-2500}$	$\mathbf{C_{tr}}$ adaptation terms, freq. range 200–2500 Hz	Same as C	10
$C_{tr,mod}$	Modified suggested spectrum based on C_{tr}	Not standardized	11
C_{opt}	Optimal spectrum adaptation term calculated in order to adapt sound reduction index curves to associate better to subjective responses	Not standardized	9,13

Table 2. Evaluation of the presented studies according to selected criteria.

Reference	Publication type[a]	Strength of association	Consistency	Specificity	Temporality	Biological gradient	Plausibility	Coherence	Experiment design	Analogy
Rychtáriková et al.[3]	++	+	+	+	+	+	+	+	+	+
Rychtáriková et al.[4]	+++	++	+	++	++	+	+	+	+	+
Monteiro et al.[5]	+++	++	++	++	++	+	++	++	++	++
Rychtáriková et al.[6]	+++	+	+	++	++	++	++	++	++	++
Pedersen et al.[7]	++	++	+	++	++	+	++	++	+	+
Vian et al.[8]	+++	++	+	++	++	++	++	++	++	++
Tachibana et al.[9]	+++	+	+	+	+	+	+	+	+	+
Park et al.[10]	+++	+++	++	+++	++	++	++	++	++	++
Park and Bradley[11]	+++	+++	++	+++	++	++	++	++	++	++
Hongisto et al.[12]	+++	+++	++	+++	++	+++	++	++	+++	++
Virjonen et al.[13]	+++	+++	++	+++	++	+++	++	++	+++	++

[a]Types: scientific journal (+++), conference paper (++), and report (+).

Coherence. It is a condition meaning that a stated causal relationship should not contradict with other accepted results or knowledge.

Experiment. It refers to the study design parameters that guarantee a reasonable causation, like randomization.

Analogy. The possibility of having or predicting analogous effects from similar factors without total evidence.

Publication type. An additional criterion was used to rank the reviewed studies. Scientific journal papers are thoroughly peer reviewed, while conference papers are usually less well reviewed. There are study reports from research organizations that may be scientifically well conducted but not reviewed at all. There are others, for example, unofficial reports, which are excluded. Thus, publications were evaluated as scientific journal (+++), conference paper (++), and report (+).

The included studies were evaluated by the authors of this article. In Table 2, the evidence evaluation rating of the studies is presented according to the criteria analyzed above. In Table 3, an overview of all the selected studies can be found, which are tabulated with summary of results, study design, methods, and conclusion. Readers who require a deeper insight in specific study results or conclusions may use the references and read the original publications. Sometimes, essential information are missing from this review article if they are not reported in the publications.

Results: associations of airborne sound data to self-reported responses in laboratory tests

In Rychtáriková et al.,[3–6] a group of studies regarding the subjective perception of loudness in living environments are presented. The studies are based on rating noise types transmitted through lightweight and heavyweight wall structures, from now on denoted as LW and HW, respectively. Several wall structures were measured according to ISO 717-1, ISO 717-2 and the acquired airborne SRI spectra were used to filter different recorded noise types. Then the created samples were used in listening tests and they were randomly sorted in pairs of a heavyweight and lightweight wall case, both having the same single value but different spectra for their SRI. The test samples were presented in random order for pairwise comparisons. The participants were asked in all cases to rate the sound that was perceived as the loudest but without knowing that they actually rate noise transmission through different types of walls. In some cases, the participants reported that they would probably reply differently if the question of the test was to address the most annoying sound instead of the loudest one.[4]

Specifically, in Rychtáriková et al.,[3,4] a small sample of eight people rated 15 different sound stimuli of typical neighbor noise types (5 s each) filtered through a heavyweight wall (masonry) spectrum and a lightweight wall spectrum (gypsum boards on metal studs). Both cases of wall structures had the same single value for $R_{living} = R_w + C_{50-5000} = 52\,\text{dB}$ but different airborne SRI curves. The tested sound stimuli were not only recorded noise samples but also the inverted versions of them, that is, the reversed signals, so the sound samples were played backward. Additional noise signals were used too, which had the same spectra as the original sounds, but without semantic information (i.e. speech, music, etc.). The listeners rated as louder the sound transmitted through the heavy wall structure in most cases, except some cases including bass sounds with many present dynamics and much modulation, as commented in the article. The main objective was to evaluate the effect of frequency and time variations in loudness perception. It was indicated that modulation and semantic context

Table 3. Overview of studies' summaries.

Reference	Samples and experiment details	Variables as defined in studies	Models and results	Parameters for evaluation	Summary of results
Rychtáriková et al.[3,4]	8 participants in a listening test (age span: 22–63) 30 sound samples tested	*Independent*: 15 different stimuli (neighbor noise, of sounds filtered through 2 types of wall airborne SRI spectra: a heavyweight wall (HW) a lightweight wall (LW) of the same index value $R_{living} = R_W + C_{50-5000} = 52\,\text{dB}$ *Dependent*: V1: perceived loudness of participants	Pairwise comparison test of sound stimuli	No details provided	LW sound samples were rated as less loud than HW filtered samples, except a case of movie sound reproduction $R_W + C_{50-5000}$ does not represent subjective perception of living noise through walls; this descriptor emphasizes on low frequencies
Monteiro et al.[5]	33 participants, mostly students in a listening test (12 females, 21 males) 900 sound samples tested	*Independent*: 90 pairs of sound samples (pink noise signals) filtered through different types of airborne sound reduction index (SRI) spectra: 5 heavyweight walls (HW) 5 lightweight walls (LW) with the same $R_{A,50-5000}$ index but R_W curves *Dependent*: V1: perceived loudness of participants	Pairwise comparison test (1HW–1LW with the same $R_{A,50-5000}$ but different R_w) Ranking by mode (RbM) Ranking by Q Score (RbQS)	Ranking and cumulative cumulative matrix outputs presented Null hypothesis H_0 : LW sounds rated louder than HW sounds proven false within 95% CI using t-test	LW sound samples were rated as less loud than HW filtered samples Wall types representative of European structures $R_{A,50-5000}$ does not reflect subjective perception and offers worse correlation than $R_W + C$ to the rankings examined
Rychtáriková et al.[6]	39 subjects in a listening test (14 females, 25 males) 128 sound samples tested	*Independent*: 64 different stimuli (everyday neighbor noise, 5 s each) of sounds filtered through 2 types of wall airborne SRI spectra: a heavyweight wall (HW) a lightweight wall (LW) of the same index value $R_W + C_{50-5000} = 52\,\text{dB}$ *Dependent*: V1: perceived loudness of participants with interview	Two-alternative forced-choice task (2AFC) of sound stimuli in random pairwise comparisons	No details provided	LW sound samples were rated as less loud than HW filtered samples, except a case of movie sound reproduction $R_W + C_{50-5000}$ does not represent subjective perception of living noise through walls; this descriptor emphasizes on low frequencies
Pedersen et al.[7]	22 participants in a home listening test with self-adjustment of volume as calibration (6 female, 18 male, age span: 26–62) 24 sound samples tested	*Independent*: 4 neighbor noise types (20 s) sounds filtered through six types of wall airborne SRI spectra *Dependent*: V1: annoyance response of participants	*Dose–response regression* curves of: L_{Aeq} to V1 R'_w to V1	*Coefficients*: $R^2 = 0.95$ $R^2 = 0.98$	Online survey test is feasible Average annoyance response highly associated with L_{Aeq} sound pressure levels and greatly associated with R'_w

(Continued)

Table 3. (Continued)

Reference	Samples and experiment details	Variables as defined in studies	Models and results	Parameters for evaluation	Summary of results
Vian et al.[8]	24 participants in a listening test (14 females, 10 males, age: 18–43) 144 sound samples tested	*Independent*: 12 different stimuli (music sound samples) of sounds filtered through 12 types of electronically synthesized wall airborne SRI spectra *Dependent*: V1: annoyance response of participants	Analysis of variance (ANOVA) to test H_0: differences insignificant among test samples *Correlation analysis for V1 and*: The slopes of the SRI curves The A-weighted band spectra (40 Hz–10 kHz) The A-weighted band spectra (125 Hz–4 kHz)	*Coefficients*: H_0 was rejected ($p < 0.01$) 95% CI ($\alpha = 0.05$) $r = -0.84$, $R^2 = 0.71$ $r = 0.48$, $R^2 = 0.23$ $r = 0.58$, $R^2 = 0.33$	Subjective annoyance is better associated with samples of A-weighted spectra 125 Hz–4 kHz than 40 Hz–10 kHz The slope of the SRI spectra and the dips in the curves found related to different responses Music samples with semantic context (words in a language that listeners can understand) were more annoying than without
Tachibana et al.[9]	8 male students in a listening test 33 sound samples tested	*Independent*: 3 different stimuli (white or pink noise filtered with different slopes) filtered through 11 types of electrically synthesized wall airborne SRI spectra *Measures*: L_A, LL, PL, NC, PNC, $\overline{L}_{63-4000}$, $\overline{L}_{125-4000}$	*Method of adjustment by subject*	No details provided	$\overline{L}_{63-4000}$ showed the best correlation with loudness adjustments Perceived level PL had good correlation as well
Park et al.[10]	15 participants in a listening test 100 sound samples tested	*Independent*: 5 Harvard speech sentence samples filtered through 12 types of electronically synthesized wall airborne SRI spectra based on real measured characteristics *Dependent*: V1: rated speech intelligibility of participants	*Regression models with Boltzmann equations*: V1 to: averaged $TL_{200-2500}$ $R_{w,200-2500}$ $R_w + C_{tr,100-3150}$ $R_w + C_{tr,200-2500}$ $R_w + C_{opt}$	*Coefficients*: All results statistically significant ($p < 0.05$) $r = -0.98$, $R^2 = 0.959$ $r = -0.96$, $R^2 = 0.922$ $r = -0.74$, $R^2 = 0.542$ $r = -0.92$, $R^2 = 0.842$ $r = -0.98$, $R^2 = 0.957$	Low association for most common indices STC, STC_{no8}, R_w, $R_w + C_{100-3150}$, $R_w + C_{tr,100-3150}$, but very high for mean $TL_{200-2500}$, $R_{w,200-2500}$ and a tested $R_w + C_{opt}$ The subjective speech intelligibility decreases when low frequencies included
Park and Bradley[11]	30 subjects in 2 listening tests (10 subjects for the annoyance test; 20 for the loudness test) 120 sound samples tested	*Independent*: 3 music and 3 speech samples Filtered through 20 types of electronically synthesized wall airborne SRI spectra based on real measured characteristics *Dependent*: V1: Mean annoyance response V2: Mean loudness response V3: Mean audibility response	*Regression models with Boltzmann equations*: V1 (annoyance) to: STC R_w $R_w + C_{tr(100-3150)}$ $R_w + C_{tr,mod}$ STC R_w $R_w + C_{tr(100-3150)}$ $R_w + C_{tr,mod}$ STC R_w $R_w + C_{tr(100-3150)}$ $R_w + C_{tr,mod}$	*Coefficients*: All results statistically significant ($p < 0.01$) (s: speech, m: music) s: $R^2 = 0.856$, m: $R^2 = 0.728$ s: $R^2 = 0.890$, m: $R^2 = 0.798$ s: $R^2 = 0.566$, m: $R^2 = 0.950$ s: $R^2 = 0.541$, m: $R^2 = 0.983$ s: $R^2 = 0.886$, m: $R^2 = 0.734$ s: $R^2 = 0.933$, m: $R^2 = 0.779$ s: $R^2 = 0.676$, m: $R^2 = 0.970$ s: $R^2 = 0.634$, m: $R^2 = 0.991$ s: $R^2 = 0.968$, m: $R^2 = 0.452$ s: $R^2 = 0.971$, m: $R^2 = 0.526$ s: $R^2 = 0.903$, m: $R^2 = 0.757$ s: $R^2 = 0.853$, m: $R^2 = 0.920$	Both and predictors were associated more with speech sounds than music sounds Overall trends for the regression equations between annoyance and loudness responses similar Few descriptors were strongly related to all response variables (V1–V3) while there were differentiations

Table 3. (Continued)

Reference	Samples and experiment details	Variables as defined in studies	Models and results	Parameters for evaluation	Summary of results
Hongisto et al.[12]	59 subjects in a listening test (19 males, 40 females, age 20–43) 54 sound samples tested	*Independent*: 6 sound samples (living sounds) filtered through 9 types of wall airborne SRI spectra. *Dependent*: V1: mean loudness response V2: mean disturbance response V3: mean acceptability response	*Regression models*: V1 (loudness) to: R_w STC_{no8} $R_w + C_{100-3150}$ $R_w + C_{100-5000}$ $R_w + C_{50-3150}$ $R_w + C_{50-5000}$ R_{speech} V2 (disturbance) to: R_w STC_{no8} R_{speech} R_w STC_{no8} R_{speech}	*Coefficients*: All results statistically significant ($p < 0.05$) $R^2 = 0.83$ $R^2 = 0.85$ $R^2 = 0.92$ (music only) $R^2 = 0.93$ (music only) $R^2 = 0.93$ (music only) $R^2 = 0.93$ (music only) $R^2 = 0.80$ $R^2 = 0.84$ $R^2 = 0.87$ $R^2 = 0.85$ $R^2 = 0.83$ $R^2 = 0.87$ $R^2 = 0.88$	Single number quantities (SNQs) including the extended range at low frequencies of 50–80 Hz performed worse than the SNQs without it Subjective responses for living sound types with flat spectrum seems to be predicted best by, and SNQs which ignore frequencies below 100 Hz Subjective responses for music (bass sounds) were best associated with spectra including low frequencies
Virjonen et al.[13]	Reused data from Jeon et al.[21] 59 subjects in a listening test (19 males, 40 females, age 20–43)	*Independent*: same data as [R8] *Dependent*: mean disturbance responses	*Regression models*: $R_w + C_{opt}$ to disturbance from: S1: guitar S2: music (traffic) S3: music (living) S4: baby cry S5: loud speech S6: dog bark	*Coefficients*: All results statistically significant ($p < 0.05$) $R^2 = 0.96$ $R^2 = 0.66$ $R^2 = 0.92$ $R^2 = 0.57$ $R^2 = 0.94$ $R^2 = 0.74$	$R_w + C_{opt}$ is developed as a SNQ that would explain the disturbance in the range of 50–5000 Hz better than any SNQ Finally, it provides better association for most sound types tested than the usual standardized descriptors

play an important role in loudness perception, especially when there is dominant low-frequency content. Time variations with several minima and maxima were found important to make people perceive a sound as loud. The metric of loudness is commented to overestimate sometimes the expected perceived loudness, due to high influence at the dominant low-frequency bands.

In Monteiro et al.,[5] a bigger listening test was conducted in Belgium and Spain with 33 participants (21 females, 12 males) where 90 pairs of sound samples were used to test the descriptor $R_{A,50-5000}$ and compare it to perceived loudness. Pink noise signals filtered through 10 different types of walls were used, which were presented to the participants in five pairs: each pair included a HW case and a LW. In every pair comparison, both wall types had the same $R_{A,50-5000}$ single value but different airborne sound reduction spectra. All 10 cases of walls were compared to each other twice in randomly formed pairs. The stimuli filtered through the five LW cases were rated as less loud than the five HW cases and the wall types used are reported as representative of European wall structures in the study. A t-test was performed indicating that the listeners perceived a difference between the test pairs of sounds within 95% CI. In some cases, noise sounds transmitted through the LW walls were considered less loud even while compared to the noise sounds through HW with higher single value R_w but the same $R_{A,50-5000}$. It is concluded that $R_{A,50-5000}$ does not associate well with subjective loudness perception. That descriptor is also reported to offer worse correlation than standardized $R_w + C$ (frequency range 100–3150 Hz) but no test parameters are provided for this.

Then, in Rychtáriková et al.,[6] another listening test was performed using 64 typical everyday sounds, recorded live during 2 weeks in 10 selected living rooms of apartments in Austrian buildings. The sounds were again filtered through a heavyweight and a lightweight wall sound reduction spectrum, forming pairwise comparisons for 39 participants (14 women and 25 men). Most responses considered louder the transmission through the heavyweight wall type as before in Rychtáriková et al.[3] In few cases, where sounds through lightweight wall types were considered louder, they included low-frequency content extremely amplified by electronic devices as reported. The LW sound reduction was better than the HW in the middle frequency range of 100–3150 Hz. Then 12 of the participants were deployed, to test the hypothesis whether A-weighting in SPL is adequate when evaluating everyday living noise types, due to low weighted sound levels. The subjects reported to perceive low frequencies less loud in low SPL compared to high SPL. Calibration and background noise levels are reported as crucial parameters for the reliability of a listening test. Temporal amplitude modulations in the test sounds are stressed as important as well. Summing up, it is indicated in all the above studies[3–6] that $R_{living} = R_W + C_{50-5000}$ is not an adequate descriptor of airborne sound performance of walls regarding the subjective perception of loudness. The explanation provided is due to the high influence of low-frequency content in the frequency adaptation terms.

In Pedersen et al.,[7] 22 persons from the COST TU0901 action took part in an online listening test, testing 24 sound stimuli at their home computer setup with headphones. Four typical neighbor noise types filtered through the airborne SRI curves of six usual various types of walls were assessed. The results indicated a high association ($R^2 = 0.95$) between the average annoyance response and the L_{Aeq} SPL of the sound samples after filtering. Great association with $R^2 = 0.98$ was reported also between the average annoyance response and the R'_w apparent SRI levels. However, the conditions of this test might seriously deviate from controlled laboratory conditions, since there is no calibration except from a self-adjustment in volume of the users. In addition, the study reports that some sound samples were radically amplified up to 14 dB so as to be definitely audible in the online test.

In Vian et al.,[8] a listening experiment for the evaluation of French regulation toward airborne sound insulation levels was conducted. Twenty-four participants took part in a laboratory test (14 females, 10 males, age span: 18–43). They reported their annoyance on 12 music sound stimuli which were filtered through 12 electronically synthesized wall SRI curves. The experiment was based on an incomplete factorial design, so from the whole 144 test samples, 1/3 was assessed by every subject. ANOVA was used to test the distinguishability between the samples (significant differences with $p < 0.01$). Newman–Keuls multiple-means comparison was used for grouping and ranking the annoyance responses. That comparison showed that slope and dips in the SRI curves, as well as the bandwidth and character of the sounds, have statistically important effects on the self-reported annoyance. It is concluded that an increasing slope of the insulation curve (i.e. more reduction in higher frequencies) leads to less annoyance. Then, a correlation analysis proved that there is a strong relation between the slopes of the SRI curves and the reported annoyance ($r = -0.85$, $R^2 = 0.72$, 95% CI). It is reported that subjective annoyance is better associated with samples with A-weighted spectra of 125 Hz–4 kHz ($r = 0.58$, $R^2 = 0.33$) instead of 40 Hz–10 kHz ($r = 0.48$, $R^2 = 0.23$) within 95% CI. In addition, noise from neighbors' speech in both French and English was assessed by French subjects in this test: the intelligibility of the sounds was found important, meaning that when there is a semantic context in the noise, the annoyance is bigger.

In Tachibana et al.,[9] a listening test took place for setting up a method for the evaluation of airborne sound insulation testing different measures. A limited sample of eight university students tested three different types of artificial noise sounds. Specifically, white or pink noise was filtered through various artificial frequency spectra of walls, based on real frequency spectra. The sound stimuli were evaluated by self-adjustment, meaning that the subjects used reference sounds to adjust the amplitude of test stimuli until they perceived every test sample as equally loud to the reference. The point of subjective equality (PSE) was used in that test for the adjustments. Many loudness measures were mentioned to have been tested such as the A-weighted SPL L_A, the loudness level LL, the perceived level PL, the noise criteria NC, and the preferred noise criteria PNC. As concluded in that article, the SPL weighted from 63 Hz: $\bar{L}_{63-4000}$ showed the best correlation with loudness adjustments. It is also mentioned that perceived level PL had good correlation as well. However, lack of statistical test parameters in the paper and the small sample size make the outcome of this study unreliable.

In Park et al.,[10] a listening experiment for the evaluation of airborne sound insulation SNQs regarding speech intelligibility was conducted with 15 subjects (participants). A total of 100 sound samples was tested consisting of five Harvard speech test sentences filtered through 20 different types of wall airborne sound reduction spectra; the spectra were synthesized but based on real measured characteristics. Different measures were explored in terms of best-fitting regression curves (using Boltzmann's equations) to the self-reported speech intelligibility. The comparison is a bit different in this study: good speech intelligibility corresponds to bad sound insulation performance and vice versa. Thus, a low intelligibility in the test would predict a sufficient airborne sound reduction of the test walls. The statistical associations of the most common standardized measures: STC, STC_{no8}, R_w, $R_w + C_{100-3150}$, $R_w + C_{tr,100-3150}$ with the subjective intelligibility ratings were found weak in overall, having acquired determination coefficients R^2 of 0.510, 0.661, 0.542, 0.359, and 0.205, respectively.

It was concluded that the examined descriptors are influenced plenty by the frequency range. Thus when low frequencies are included in the calculations correlation with speech intelligibility decreases because they do not contain useful information on the transmitted speech; the low frequencies do not contain information on the transmitted speech. In a parametric analysis included, the authors demonstrate that the highest correlation can be acquired when using the arithmetic average TL with the restricted frequency range of 200–2500 Hz: $TL_{200-2500}$ ($r = -0.98$, $R^2 = 0.959$). For the standardized $R_{w,200-2500}$ (with the same restricted range), a similarly great association was acquired ($R^2 = 0.922$), while they are not so good for descriptors with wider frequency range:

$R_w + C_{tr,100-3150}$ ($R^2=0.542$) and $R_w + C_{tr,200-2500}$ ($R^2=0.842$). Finally, a spectrum adaptation based on a speech rating contour a (band pass filter for speech) was suggested and tested: C_{opt}. When added to R_w, there was a great association between the self-reported speech intelligibility and the indicator: $R_w + C_{opt}$ ($r=-0.98$, $R^2=0.957$). The descriptors which involve arithmetic averages in frequency bands relevant to speech (200 Hz–2.5 kHz) were reported as the best associated with the intelligibility responses. All the presented results were found statistically significant ($p<0.05$).

A continuation of this research is presented in Park and Bradley[11] for the evaluation of the existing standardized airborne sound insulation measures for annoyance, loudness, and audibility. Another listening test was conducted with the same methodology as Park et al.,[10] this time using three speech samples and three music samples, filtered through 20 various wall SRI spectra. The measured walls had a spectrum of STC values of 34–58 dB. The total of 120 speech and music samples were presented in random orders and rated in two occasions: one test regarding the annoyance degree (10 participants, rating scale 1 (Not at all) to 7 (Extremely)) and a second test rating loudness perception (another 20 participants, rating scale 0 (Not audible) to 7 (Extremely)). The results were again evaluated in terms of average annoyance or loudness response regression fit to standard SNQs (using Boltzmann's equations) again.

The associations observed for self-reported mean annoyance were strong in relation to STC (speech: $R^2=0.856$, music: $R^2=0.728$) and a bit higher for the mean annoyance and R_w (speech: $R^2=0.890$, music: $R^2=0.798$). As for the loudness test, the associations were just good between the self-reported mean loudness ratings and STC (speech: $R^2=0.886$, music: $R^2=0.734$) and better for the association of loudness and R_w (speech: $R^2=0.933$, music: $R^2=0.779$). Different spectrum adaptation terms were added to R_w offering some improvements for the association with self-reported annoyance: $R_w + C_{tr(100-3150)}$ (speech: $R^2=0.566$, music: $R^2=0.950$) and loudness: $R_w + C_{tr(100-3150)}$ (speech: $R^2=0.676$, music: $R^2=0.970$) which worked well only for the music cases. The best association in the study was reported with the use of a new suggested adaptation term $C_{tr,mod}$, after modifying the C_{tr} spectrum to emphasize more on high frequencies around 1 kHz. Again the association was sufficient only for the music sound cases in relation to annoyance: $R_w + C_{tr,mod}$ (speech: $R^2=0.541$, music: $R^2=0.983$) and loudness $R_w + C_{tr,mod}$ (speech: $R^2=0.634$, music: $R^2=0.991$).

Finally, for the audibility test, the previous values of loudness responses equal to 0 were used to define the state of "not audible." The association of audibility to STC was good for speech only (speech: $R^2=0.968$, music: $R^2=0.452$); the same applies to the relation to R_w with better values (speech: $R^2=0.971$, music: $R^2=0.526$). Improvements were made for R_w results for music only when adding the spectrum adaptation terms (opposite results for speech): $R_w + C$ (speech: $R^2=0.903$, music: $R^2=0.757$) and $R_w + C_{tr(100-3150)}$ (speech: $R^2=0.853$, music: $R^2=0.920$). All results for the determination coefficients were reported statistically significant ($p<0.01$) in the study. The overall trends for the regression equations between annoyance and loudness responses were reported very similar indicating very small differences between the two measures. Summing up, few descriptors were strongly associated with all tested variables of subjective responses. Consequently, it is concluded that different descriptors work better for different kinds of noise.

A similar study was conducted in Finland[12] regarding the subjective evaluation of standardized SNQs characterizing airborne sound insulation of building elements, as stated in ISO 717-1[41] and ASTM E413.[52] A listening test took place including 59 subjects (19 males, 40 females, age 20–43; mean age: 27 years) who rated a set of six recorded sounds of typical noise types found in residential buildings: guitar sound, two music samples, speech, baby cry and barking dog. The music samples were modified to correspond to the traffic and the living spectrum of the relevant adaptation terms according to ISO 717-1. The test sound samples were filtered according to airborne SRI spectra of nine different wall structures measured in laboratory conditions (54 test samples in total, R_w values range 48–75 dB). The subjective measures used were loudness, disturbance and acceptability ratings (scale 0 (Not at all) to 10 (Extremely)) formulated in simple questions. Linear regression analysis was performed between the averaged subjective responses and the SNQs: the determination coefficients (average R^2 for all six sound samples) were reported, as individual or averaged values. Mostly, the latter are presented in this review.

An initial conclusion was that SNQs including the extended frequency range at low frequencies of 50–80 Hz performed worse than the SNQs without it, which was derived in previously presented studies as well.[10,11] The SNQ of STC_{no8} predicted loudness ($R^2 = 0.85$) and disturbance ($R^2 = 0.87$) response better than every other, while R_{speech} ($R^2 = 0.88$) was the best metric to predict acceptability. Another conclusion is that $R_w + C_{tr,50\text{–}3150}$ and $R_w + C_{tr,50\text{–}5000}$ were the most inefficient predictors in general with coefficients R^2 less than 0.7. $C_{tr,50\text{–}5000}$ is the A-weighted urban traffic noise adaptation spectrum of ISO 717-1. Different SNQs had different prediction efficiencies for the various sound types tested, due to emphasis on different frequencies. For the case of music sounds (which included traffic noise adaptation spectrum) with dominant bass frequency context, the descriptors $R_w + C_{100\text{–}3150}$ ($R^2 = 0.92$), $R_w + C_{100\text{–}5000}$ ($R^2 = 0.93$), $R_w + C_{50\text{–}3150}$ ($R^2 = 0.93$) and $R_w + C_{50\text{–}5000}$ ($R^2 = 0.93$) predicted the loudness response best, whereas the last two SNQs predicted best also the disturbance and acceptability ratings contrary to some previous studies.[12,13] Overall, the response for living sound types with flat spectrum seems to be predicted best by R_w, STC, and SNQs which ignore frequencies below 100 Hz showing R^2 values around 0.9, while for noise types with dominant higher frequencies, such as baby cry and dog bark the best predictors were R_{speech}, STC, and STC_{no8}. All the presented results were found statistically significant ($p < 0.05$).

Additionally, in Virjonen et al.[13] which is a continuation of the previous study,[12] the same data of the six sound samples and the subjective ratings were utilized in order to create a SNQ measure which would predict and explain the disturbance in the frequency range of 50–5000 Hz better than all other standardized SNQs. A certain algorithm was developed for optimal fit between mean subjective ratings and the optimized averaged reference spectra. The outcome was another descriptor with a new adaptation spectrum: $R_w + C_{opt}$. That finally works as expected in general, specifically well in association with guitar sound with $R^2 = 0.96$, music (living spectrum as stated in Hongisto et al.[12]) with $R^2 = 0.92$, and loud speech with $R^2 = 0.94$. The adaptation term C_{opt} is utilized for the averaged spectra of noise types tested, while C_{Si} was tested for the individual noise types offering for every specific sound optimization a determination coefficient of $R^2 = 0.95$ in all individual cases. All the presented results were found again statistically significant ($p < 0.05$).

Discussion

There can be strong associations between airborne sound data and self-reported responses of annoyance and loudness[10–13] in general. However, the statistical associations were weak in overall when intelligibility was used as a measure of perception.[10] The measures of self-reported audibility and acceptability were also used once, in Park and Bradley[11] and Virjonen et al.,[13] respectively. It is also highlighted in a study that few differences were found between loudness and annoyance in the subjective responses.[11]

Most laboratory studies based on airborne sound data examine the horizontal sound transmission, that is, the R_w of walls. When it comes to vertical sound transmission, most studies deal with impact sound data as a priority, which is critical for propagation through floors and it has been found to be the most disturbing noise type in residential buildings.[14,27–35] Therefore, it seems that airborne sound studies remain supplementary to impact sound for researching vertical noise transmission.

The airborne sound studies testing transmission through walls conclude that subjects perceive noise through heavyweight walls as louder than the ones transmitted through lightweight walls.[3–6] The airborne sound reduction frequency spectra of lightweight walls are usually better than heavyweight ones, except the low-frequency range. The effect of frequency and time variations in subjective perception was also highlighted in Rychtáriková et al.:[6] it was indicated that modulation and semantic context (e.g. speech) affect loudness perception. The latter observation is also supported in Vian et al.[8] where the intelligibility of the sounds was found important: annoyance perception is affected by semantic context in the noise sounds.

The inclusion of low frequencies (down to 50 Hz) in the measurements and derivation of descriptors seems to be an important issue in some of the reviewed studies. In the studies,[3–6] the descriptors with extended spectrum adaptation terms like $R_W + C_{50-5000}$ do not associate sufficiently with the subjective annoyance of residents because such descriptors emphasize a lot on low frequencies. The same conclusion is supported in literature,[8–12] while in Park et al.[10] a limited frequency range of 200–2500 Hz is suggested to be optimal for association of subjective intelligibility of speech sounds.

The previous conclusions from studies[3–6,8–12] are contradictory to the general trend in impact sound measurements and descriptors: inclusion of low-frequency spectra down to 50 Hz (even down to 20–25 Hz) in impact sound data is considered necessary to achieve sufficient association with self-reported responses.[27–35] However, sometimes the same is stated in studies for airborne sound: in Park and Bradley,[11] many associations were very good between subjective annoyance or loudness and SRI descriptors for various stimuli with low-frequency content too. In addition, in Hongisto et al.,[12] descriptors such as R_w and STC with extended frequency range down to 50 Hz are suggested perform best for prediction of subjective annoyance and loudness to music stimuli (but not the other sounds tested).

Furthermore, the different types of sound stimuli are highlighted as an important parameter in some studies[10,13] because speech sounds have more high-frequency content while low frequencies are dominant in music sound stimuli. There are variations of course, for the cases of different sounds tested and responses. Therefore, in many studies, some of the descriptors work for certain types of sounds only, for example, in Park and Bradley[11] and Virjonen et al.,[13] the descriptors with extended spectra to low frequencies associate very well with music but not with speech in most cases. In Virjonen et al.[13] the descriptors that relate well to speech do not relate that well for music or other living sounds.

In overall, many studies attempt to find a descriptor for airborne sound that would predict well the general noise annoyance perception. But there is not a certain descriptor that seems to associate great with every type of sound. This review demonstrates that different descriptors work better for various stimuli. However, in Virjonen et al.[13] and Rasmussen and Rindel,[14] a spectrum adaptation term is suggested to formulate the measure: $R_w + C_{opt}$ which predicts well most airborne sound types (except baby cry) within the full measurement spectrum of 50–5000 Hz and it is different to the standardized adaptation term $C_{50-5000}$.

In some cases, the study design parameters are problematic: the sample size of listening tests can be small as in Pedersen et al.[7] and Vian et al.[8] or extremely small as in literature.[3,4,9,10] However more subjects would be essential for a sufficient sample size and thus further inference of the results from such experiments; conclusions are weak when they are based on a small sample. Most of the studies have a good level of presentation and evaluation of evidence as can be seen in Table 2. Many statistical evaluations took place to compare and relate results between objective and subjective data, some were incomplete with missing parameters, and tests of significance or some study details were not reported at all.[3,4,9] It would be essential for every study to have a method presentation, study design, and sufficient tabulation of relevant parameters.

Conclusion

This review shows that subjective response to airborne sound in dwellings is complicated: it can be predicted well in some cases but not always. Standardized SNQs and alternative descriptors for airborne sound have been evaluated and associated sufficiently with subjective responses collected in laboratory listening tests. The type of sound stimulus is significant because different stimuli with various frequency spectra correspond better to different descriptors. Inclusion of low frequencies down to 50 Hz in airborne sound measurements seems to be problematic: it leads only certain metrics to associate better with self-reported responses.

Consequently, all descriptors do not associate well with all kinds of airborne sound stimuli in living environments. The descriptors with low-frequency adaptation spectra relate better to music sound sources with dominant low-frequency content while the opposite applies to sound stimuli of speech. Finally, there is no overall indicator to work best for all kinds of airborne sound types in dwellings, but few suggestions of frequency adaptation spectra work very well for that reason. Additional properties of noise signals such as frequency and time modulation and semantic context are indicated to play a role in subjective perception of annoyance or loudness.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This article was written within the research project "Acoustic Comfort in Building Apartments" funded by Saint-Gobain Weber.

References

1. Vardaxis N-G, Bard D and Waye KP. Review of acoustic comfort evaluation in dwellings—part I: associations of acoustic field data to subjective responses from building surveys. *Build Acoust* 2018; 25: 151–170.
2. Vardaxis N-G and Bard D. Review of acoustic comfort evaluation in dwellings—part II: impact sound data associated to subjective responses in laboratory tests. *Build Acoust* 2018; 25: 171–192.
3. Rychtáriková M, Müllner H, Urbán D, et al. Influence of temporal and spectral features of neighbour's noise on perception of its loudness. In: *Proceedings of the Euronoise 2013*, Innsbruck, 15–18 September 2013.
4. Rychtáriková M, Roozen B, Müllner H, et al. Listening test experiments for comparisons of sound transmitted through light weight and heavy weight walls. *Akustika* 2013; 19: 8–13.
5. Monteiro C, Machimbarrena M, De la Prida D, et al. Subjective and objective acoustic performance ranking of heavy and light weight walls. *Appl Acoust* 2016; 110: 268–279.
6. Rychtáriková M, Muellner H, Chmelík V, et al. Perceived loudness of neighbour sounds heard through heavy and light-weight walls with equal $R_w + C_{50-5000}$. *Acta Acust United Ac* 2016; 102(1): 58–66.
7. Pedersen TH, Antunes S and Rasmussen B. Online listening tests on sound insulation of walls—a feasibility study. In: *Proceedings of the Euronoise 2012*, Prague, 10–13 June 2012.

8. Vian J-P, Danner WF and Bauer JW. Assessment of significant acoustical parameters for rating sound insulation of party walls. *J Acoust Soc Am* 1983; 73(4): 1236–1243.
9. Tachibana H, Hamado Y and Sato F. Loudness evaluation of sounds transmitted through walls—basic experiments with artificial sounds. *J Sound Vib* 1988; 127(3): 499–506.
10. Park HK, Bradley JS and Gover BN. Evaluating airborne sound insulation in terms of speech intelligibility. *J Acoust Soc Am* 2008; 123(3): 1458–1471.
11. Park HK and Bradley JS. Evaluating standard airborne sound insulation measures in terms of annoyance, loudness and audibility ratings. *J Acoust Soc Am* 2009; 126(1): 208–219.
12. Hongisto V, Oliva D and Keränen J. Subjective and objective rating of airborne sound insulation—living sounds. *Acta Acust United Ac* 2014; 100: 848–864.
13. Virjonen P, Hongisto V and Oliva D. Optimized single-number quantity for rating the airborne sound insulation of constructions: living sounds. *J Acoust Soc Am* 2016; 160(4): 4428.
14. Rasmussen B and Rindel JH. Concepts for evaluation of sound insulation of dwellings—from chaos to consensus? In: *Proceedings of the forum acusticum 2005*, Budapest, 29 August–2 September 2005.
15. Yeon J. Subjective evaluation of floor impact noise based on the model of ACF/IACF. *J Sound Vib* 2001; 241(1): 147–155.
16. Yeon JY and Jeong JH. Objective and subjective evaluation of floor impact noise. *J Temp Des Archit Environ* 2002; 2(1): 20–28.
17. Jeon JY, Jeong JH, Vorländer M, et al. Evaluation of floor impact sound insulation in reinforced concrete buildings. *Acta Acust United Ac* 2004; 90: 313–318.
18. Jeon JY, Ryu JK, Jeong JH, et al. Review of impact ball in evaluating floor impact sound. *Acta Acust United Ac* 2006; 92: 777–786.
19. Lee PJ, Kim JH and Jeon JY. Psychoacoustical characteristics of impact ball sounds on concrete floors. *Acta Acust United Ac* 2009; 95: 707–717.
20. Jeon JY and Sato S. Annoyance caused by heavyweight floor impact sounds in relation to the autocorrelation function and sound quality metrics. *J Sound Vib* 2008; 311: 767–785.
21. Jeon JY, Lee PJ, Kim JH, et al. Subjective evaluation of heavy-weight floor impact sounds in relation to spatial characteristics. *J Acoust Soc Am* 2009; 125(5): 2987–2994.
22. Kim JH, Ryu JK and Jeon JY. Effect of temporal decay on perception of heavy-weight floor impact sounds. *J Acoust Soc Am* 2013; 134(4): 2730–2738.
23. Jeon JY and Oh SM. Psychoacoustical evaluation of heavyweight floor impact sounds in apartment buildings. In: *Proceedings of the inter-noise 2014*, Melbourne, VIC, Australia, 16–19 November 2014.
24. Ryu J, Sato H, Kurakata K, et al. Relation between annoyance and single-number quantities for rating heavy-weight floor impact sound insulation in wooden houses. *J Acoust Soc Am* 2011; 129(5): 3047–3055.
25. Gover BN, Bradley J, Schoenwald S, et al. Subjective ranking of footstep and low-frequency impact sounds on lightweight wood-framed floor assemblies. In: *Proceedings of the forum Acusticum 2011*, Aalborg, 27 June–1 July 2011.
26. Gover BN, Bradley JS, Zeitler B, et al. 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 2011*, Osaka, Japan, 5–7 September 2011.
27. Späh M, Hagberg K, Bartlomé O, et al. Subjective and objective evaluation of impact noise sources in wooden buildings. *Build Acoust* 2013; 20(3): 193–214.
28. Kylliäinen M, Hongisto V, Oliva D, et al. A laboratory listening experiment on subjective and objective rating of impact sound insulation of concrete floors. In: *Proceedings of the inter-noise 2016*, Hamburg, 21–24 August 2016.
29. Kylliäinen M, Hongisto V, Oliva D, et al. Subjective and objective rating of impact sound insulation of a concrete floor with various coverings. *Acta Acust United Ac* 2017; 103: 236–250.
30. Öqvist R, Ljunggren F and Johnsson R. Listening test of walking noise from 20 Hz in dwellings. In: *Proceedings of the inter-noise 2017, Hong Kong*, China, 7 December 2017, pp. 3935–3942. Reston, VA: Institute of Noise Control Engineering.

31. Ljunggren F, Simmons C and Hagberg K. Correlation between sound insulation and occupants' perception—proposal of alternative single number rating of impact sound. *Appl Acoust* 2014; 85: 57–68.
32. Ljunggren F, Simmons C and Hagberg K. Findings from the AkuLite project: correlation between measured vibro-acoustic parameters and subjective perception in lightweight buildings. In: *Proceedings of the Inter-noise 2013*, Innsbruck, 15–18 September 2013.
33. Simmons C and Ljunggren F. Aku20—searching for optimal single number quantities in EN ISO 717-2 correlating field measurements 20—5000 Hz to occupant's ratings of impact sounds—new findings for concrete floors. In: *Proceedings of the EuroNoise 2015*, Maastricht, 31 May–3 June 2015.
34. Ljunggren F, Simmons C and Öqvist R. Correlation between sound insulation and occupants' perception—proposal of alternative single number rating of impact sound-part II. *Appl Acoust* 2017; 123: 143–151.
35. Ljunggren F, Simmons C and Öqvist R. Evaluation of impact sound insulation from 20 Hz. In: *Proceedings of the 24th international congress on sound and vibration (ICSV24)*, London, 23–24 July 2017.
36. Guigou-Carter C, Balanant N and Villenave M. Acoustic comfort evaluation in lightweight wood-based buildings. In: *Proceedings of the forum acusticum*, Krakow, 7–12 September 2014.
37. Milford I, Høsøien CO, Løvstad A, et al. Socio-acoustic survey of sound quality in dwellings in Norway. In: *Proceedings of the inter-noise 2016*, Hamburg, 21 August 2016.
38. Høsøien CO, Rindel JH, Løvstad A, et al. Impact sound insulation and perceived sound quality. In: *Proceedings of the inter-noise 2016*, Hamburg, 21 August 2016.
39. Hagberg K. Evaluating field measurements of impact sound. *J Build Acoust* 2010; 7: 105–128.
40. Hongisto V, Mäkilä M and Suokas M. Satisfaction with sound insulation in residential dwellings—the effect of wall construction. *J Build Environ* 2015; 86: 309–320.
41. ISO 717-1:1996. Acoustics—rating of sound insulation in buildings and of buildings elements—part 1: airborne sound insulation.
42. ISO 140-3:1995. Acoustics—measurement of sound insulation in buildings and of building elements—part 3: laboratory measurements of airborne sound insulation of building elements.
43. EN 12354-1:2000. Building acoustics—estimation of acoustic performance of buildings from the performance of elements—part 1: airborne sound insulation between rooms.
44. ISO 16283-1:1998. Acoustics—field measurement of sound insulation in buildings and of building elements—part 1: airborne sound insulation.
45. ISO 140-4:1998. Acoustics—measurement of sound insulation in buildings and of building elements—part 4: field measurements of airborne sound insulation between rooms.
46. ISO 10140-2:2010. Acoustics—laboratory measurement of sound insulation of building elements—part 2: measurement of airborne sound insulation.
47. ISO 1996-1:2016. Acoustics—description, measurement and assessment of environmental noise—part 1: basic quantities and assessment procedures.
48. Stevens SS. Procedure for calculating loudness: Mark VI. *J Acoust Soc Am* 1961; 33(11): 1577–1585.
49. Stevens SS. Perceived level of noise by Mark VII and decibels (E). *J Acoust Soc Am* 1972; 51(2): 575–601.
50. Schultz TJ. Noise-criterion curves for use with the USASI preferred frequencies. *J Acoust Soc Am* 1968; 43(3): 637–638.
51. Beranek LL, Blazier WE and Figwer JJ. Preferred Noise Criterion (PNC) curves and their application to rooms. *J Acoust Soc Am* 1971; 50(5): 1223–1228.
52. ASTM E413-87:1999. Classification for rating sound insulation.
53. Rice JA. *Mathematical statistics and data analysis*. 2nd ed. Boston, MA: Cengage Learning, 2007.
54. Höfler M. The Bradford hill considerations on causality: a counterfactual perspective. *Emerg Themes Epidemiol* 2005; 2: 11.
55. Schünemann H, Hill S, Guyatt G, et al. The GRADE approach and Bradford hill's criteria for causation. *J Epidemiol Community Health* 2011; 65: 392–395.

Paper D

Published in Journal of Sustainable Architecture and Civil Engineering, Vol. 1, No. 24, 2019, p.78-89, DOI 10.5755/j01.sace.24.1.22068.

Acoustic Comfort Investigation in Residential Timber Buildings in Sweden

Delphine Bard[1,2*], Nikolaos-Georgios Vardaxis[1], Elin Sondergard[2]

[1] Lund University, LTH, Department of Technical Acoustics, John Ericssons väg 1, Lund, Sweden.
[2] Saint-Gobain Nordic & Baltic Delegation, Robert Jacobsens Vej 62A, 2300 København S Denmark.
*Corresponding author: delphine.bard@construction.lth.se

Abstract

This article presents parts of a wide survey on acoustic comfort in Swedish family buildings, specifically with focus on timber lightweight buildings. The scope of the whole research is to investigate acoustic comfort dimensions after collecting and combining data from standardized acoustic measurements and subjective responses from a questionnaire survey. Certain noise sources were reported as dominant within living environments, impact noise from neighbors being the most important. Installation noise from inside the building and outdoor low-frequency noise disturb also a lot. However, the overall level of acoustic comfort in contemporary wooden buildings seems satisfactory.

KEYWORDS: acoustic comfort, field measurements, noise annoyance, subjective responses.

Introduction

This article concerns investigation of acoustic comfort in contemporary Swedish timber buildings. The results presented are part of a wider research project about acoustic comfort in family apartments in Sweden, including timber structures as well as typical heavyweight concrete or mixed structure types (e.g. steel and concrete). To implement this study data from standardized acoustic measurements in the sample building structures were utilized. Then an acoustic survey was setup for the residents of the test buildings: they were invited to fill in a questionnaire in their living environment. The overall scope of the research project is to collect and combine acoustic data and subjective responses from residents in order to develop approaches for the concept of acoustic comfort.

The only description offered for the concept of acoustic comfort in the existing literature is the following: “a concept characterized by absence of unwanted sound, desired sounds with the right level and quality, opportunities for acoustic activities without annoying other people” as stated by Rasmussen and Rindel (2010). We would also add in that definition: “a concept with opportunities for supportive acoustic conditions according to the activities taking place”. For instance, different demands for acoustic conditions in a flat exist when residents cook, sleep, read or play the piano. Furthermore, the above statements describe how acoustic comfort is relevant to a person as a receiver of sound and a source: somebody can be disturbed by noise from others or by their own sounds or by the idea that they might disturb others around them. Consequently, there can be conflicts or discomfort due to various situations related to noise sound in living environments.

Current standardized methods for airborne sound reduction and impact noise measurements have been used to assess sound insulation of building components (ISO717 1996, ISO140 1998, ISO16283 2014, EN ISO12354 2017) but also as means to evaluate acoustic comfort in flats. As we analyzed in a review paper of relevant building acoustic surveys (Vardaxis et.al. 2018), the measured descriptors derived from the ISO standard measurements are highly associated to the subjective noise annoyance responses of the residents in multistory buildings. However, the acoustic indicators represent sound transmission between building elements, they do not represent directly any acoustic comfort index.

For this research project we have setup a questionnaire design which includes noise annoyance from several sources in buildings alongside other important variables such as: size of home, living density in flats, characterization and emotional reaction to acoustic conditions at home and demographic data. In this article we present parts of the collected data with a main focus on noise annoyance in timber buildings; we demonstrate results of the whole sample which includes concrete buildings too, for a comparison of the differences regarding the wooden structures.

Methods

Our research design includes 101 different building units (different addresses) of 34 different structures types: concrete or timber buildings and mixed structures. Thus the sample of buildings is 34 blocks (1 or more units each) with different structures: 25 HW buildings, 7 LW and 2 mixed structures: the term heavyweight (HW) refers to concrete buildings and the term lightweight (LW) refers to wooden buildings. HW have a structure with concrete beams, floor and support walls: they can have concrete panels, brick walls (any kind or brick) or prefabricated panels (concrete, heavy or light) for walls. LW have wooden beams, floor and support walls: they utilize wooden elements, light bricks or prefabricated lightweight panels for wall components.

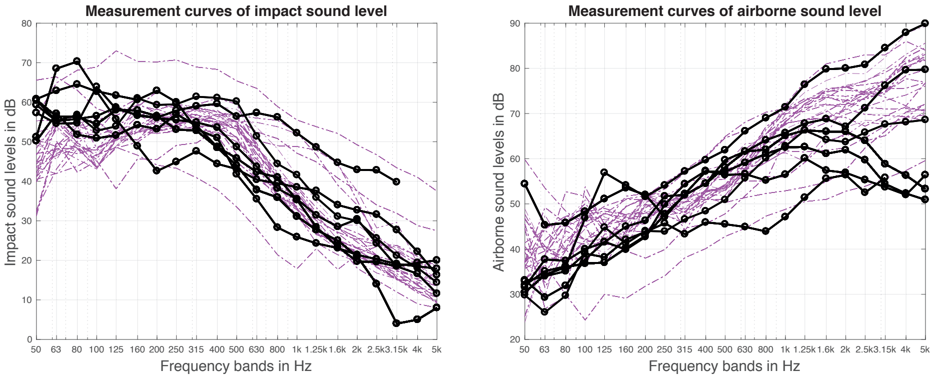


Figure 1: Impact sound levels $L'_{n,w}$ (left) and airborne sound reduction levels R'_{w} (right) for all sample buildings of the research project: HW buildings with purple lines, LW wooden buildings with bold black lines.

Following the European or ISO standards and previous research (Negreira 2016, Hagberg 2018, Ljungren et.al. 2014, Hagberg and Bard 2014), sound transmission was measured between two typical adjacent rooms, one above another, always bedrooms or living rooms, typical of the building's floor plan and representative of everyday acoustic conditions. The room above is the sending test room and the one below is the receiving test room; That acoustic data included airborne sound measurements (sound speaker source above, microphone positions below), impact sound measurements (standardized tapping machine or other impact sources above, microphone positions below) and reverberation time measurements (impulse response measurement with sound source and microphones in the same test room) for the receiving room.

Figure 1 presents the measurement curves for impact sound levels $L'_{n,w}$ and airborne sound reduction levels R'_w for all sample structures. HW concrete buildings follow a similar trend with less dispersion around that except few cases of much higher or lower performance, especially in cases of impact sound which is the most critical for acoustic comfort (Hagberg 2018, Ljungren et.al. 2014). For the LW curves the behavior is dissimilar, with wider dispersion between them in the whole frequency range for both cases of impact and airborne sound. However, the highest and lowest values in curves belong mostly to HW cases, as can be seen in Figure 1 and also Table 1.

Table 1: Single number quantities of acoustic descriptors for the sample buildings

		Impact sound index in dB			Airborne sound reduction index in dB		
		$L'_{n,w}$	$L'_{n,w}+C_{50-2500}$	$L'_{n,w}+C_{100-2500}$	R'_w	$R'_w+C_{50-3150}$	$R'_w+C_{100-3150}$
Type:	N		Mean (Range)			Mean (Range)	
Heavyweight (HW)	25	50 (38-64)	50.2 (40-65)	49.7 (39-64)	59.3 (46-67)	57.7 (44-64)	58.1 (44-65)
Lightweight (LW)	7	48.8 (45-55)	52.4 (49-59)	49.6 (47-54)	58.1 (48-68)	55.5 (48-63)	56.4 (48-65)
All structures	34	49.8 (38-64)	50.8 (40-65)	49.7 (39-64)	59 (46-68)	57.2 (44-64)	57.6 (44-65)

Table 1 presents some statistics for the single number quantities for the sample measurements, the indices for airborne and impact sound characterization calculated according to the relevant ISO standards. Note that measurements in this study have a frequency range between 50-5000Hz and the single number indices are calculated from 50 Hz, which is the standard requirement in Scandinavia. Most data were acquired by a national Swedish research database: the Green Building database. The building regulations in Sweden demand a minimum level of sound level difference of $D'_{nT,w,50}$=52 dB from the space outside to inside a dwelling and highest impact sound levels of $L'_{nT,w,50}$=56 dB. Those descriptors are equal to $R'_w+C_{50-3150}$ and $L'_{n,w}+C_{50-2500}$ respectively when no flanking transmission has been measured. However, other European countries have not that strict limits while the official requirement of the ISO standard is 100-3150Hz for airborne sound and 100-2500Hz for impact sound measurements (Boverket, 2016).

Furthermore, self-reported data was collected with the development of a social survey, using a questionnaire for the residents developed according to (ISO-15666 2003). The survey aimed to capture several aspects that we consider part of the overall acoustic comfort concept: there is special focus on targeting all possible noise types and other variables relevant to noise annoyance. The questionnaire was distributed using post mail (one copy for every test flat, a web link was provided too): an invitation letter was sent first with the questionnaire, then two reminder letters followed within a month. The questions analyzed in this article are presented in Table 2, with some statistics which refer to the subjects (residents) living in LW wooden buildings only.

The subjects sample have an age span of 18-85 years and have spent at least 12 months in their flat, which were basic requirements for the survey. Also they should have normal hearing, thus subjects who use hearing aids at home were filtered out of the data. Tenants who live on the top floor were filtered out too, since they do not have neighbors on the floor above and their perception of noise annoyance is probably different. Finally, after filtering, 85 responses for LW subjects were collected: 37 male, 45 female (3 did not report gender). The gender distribution was the same for the 375 subjects of the total sample (LW and HW) split in 43% men and 55% women. The overall response rate was 28% in both cases of LW and HW buildings. Figure 2 presents the distribution of observations in the overall research sample grouped by structure blocks, so one can see HW and LW observations together.

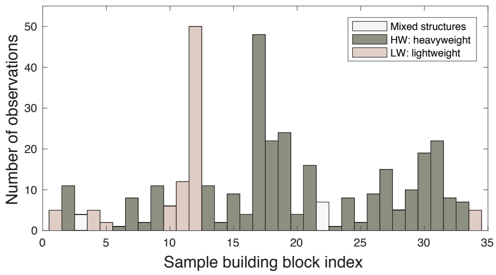


Figure 2: Histogram of the total research sample: observations grouped in building blocks and different structure types.

The distribution of our observations grouped in different structures (or building blocks) is uneven: most blocks have less than 10 observations. However, 5 HW and 1 LW blocks, have 50% of the total observations (187 out of 375). For the case of LW wooden structures, a certain structure provided 59% of the total LW sample: that was a building block of 4 building units (8 separate addresses) of the exact same wooden structure type.

Results and Discussion

Histograms of questions 1-3 are illustrated in Figure 3. As can be observed, most subjects stayed at their house for 1-5 years, about 71% while only 9% have lived for more than 10 years. That situation is indicative of mobility in Swedish apartments since there are new buildings erected and inhabited, while in parallel a shortage of house supply makes lots of tenants to rely on short-term rentals and move frequently between rented flats. For the LW cases, tenants have evenly spent from 1-10 years in the building but the wooden structures of our sample are contemporary: the oldest one was finished and occupied in 2008.

Question 2 (Fig. 3) concerns apartment size (in square meters): the distribution of this variable is close to normal, with most flats being between 60 and 80 sq., one third of the total sample. For the wooden buildings case, this is still true: 32 of the 85 LW flats are between 60-80 sq. (ca. 38%) but the overall LW data concern bigger flats. For instance, 37% of the LW flats are bigger than 80 sq. which can be justified as wooden buildings in Sweden are new and have bigger size.

The number of flat tenants is important for the parameter of living density. As illustrated in question 3 (Fig. 3) one or two persons live in most flats in both HW and LW structures, while only 20% of the cases concern 3 tenants or more in a flat. For wooden buildings, it is only 12% of flats with 3 or more tenants, while 34 persons live alone (40%).

Then, question 4 deals with the presence of children in the house, which is an important factor for the status of the tenants (family with children at home), the living density and the possible presence of noise at their own home due to children. Overall, 23% of the survey flats have children at home, while for the wooden buildings sample this percentage is almost half namely 14% (12 out of 85).

Question 5 aimed at nuisances that affect the decisions of the tenants that much as to move out from a residency. About 8% of the total subjects would consider moving out due to noise pollution in their living environment: this corresponds to a small percentage for LW buildings (only 2%) but a considerable percentage for HW concrete buildings (9%). That is a first indication that wooden multistory residencies in Sweden can offer better acoustic conditions compared to typical concrete structures, but they were also designed to fulfil higher acoustic criteria.

Table 2: Questionnaire data and initial statistics for the wooden building sample

Questions	N: replies	Mean	Std.
1. How long have you lived in your home? (years)	83	5.96	4.11
2. What is the size of your home? (in square meters)	72	80.10	16.78
3. How many people, including you, are currently living in your home?	80	1.73	0.75
4. Do you have children living with you on a regular basis? (1:No, 2:Yes)	81	1.15	0.36
5. Are you considering moving from your home due to noise pollution? (1:No, 2:Yes)	83	1.02	0.15
6. Is there any other disturbing source of noise in or close to your home that we have not addressed? (1:No, 2:Yes)	84	1.22	0.42
7. If so, please indicate the level of disturbance: (1:Not at all, 2:Slightly, 3:Moderately, 4:Very, 5:Extremely)	23	1.91	0.85
8. How pleased are you with the sound environment in your home? (1:Very pleased, 2:Fairly pleased, 3:Neither pleased or displeased, 4:Fairly displeased, 5:Very displeased)	81	1.75	1.06
9: Thinking about the last 12 months, when you are here at home…			
9.a. *How much do you think about* not disturbing your neighbours when you e.g. play music, close doors, or walk around?	82	2.34	1.09
9.b. *How disturbed/bothered* do you think your neighbours are from the noise you make? (1:Not at all, 2:Slightly, 3:Moderately, 4:Very, 5:Extremely)	82	1.26	0.58
10: Thinking about the last 12 months, when you are here at home, *with the windows and doors shut, how much* disturbed are you by:			
10.a. **Noise from machines or appliances inside the building**? (Refrigerator, freezer, washer, dryer, lift, AC, ventilation, water pipes, flushing toilets)	82	1.86	0.78
10.b. **Low-frequency noise** from a neighbour's sound system, TV or computer, coming through the walls?	82	1.21	0.51
10.c. **Low-frequency noise** from a neighbour's sound system, TV or computer, coming through the floor or ceiling?	81	1.42	0.69
10.d. **Sound of neighbours talking,** coming through the walls?	82	1.07	0.47
10.e. **Sound of neighbours talking,** coming through the floor or ceiling?	81	1.22	0.63
10.f. **Sound of neighbours walking**, slamming doors and dropping things, thuds from children playing, coming through the floor or ceiling?	82	2.04	1.01
10.g. **Sound of walking** in shared spaces of the building (staircase, hallway, etc.)?	82	1.40	0.78
10.h. **Low-frequency noise** (rumbling, muffled sound) from **outside sources such as music, traffic and ventilation**? (1:Not at all, 2:Slightly, 3:Moderately, 4:Very, 5:Extremely)	82	1.67	0.77
11: How would you rate your normal quality of sleep? (1:Very good, 2:Good, 3:Neither good or bad, 4:Bad, 5:Verybad)	82	2.26	1.05
12: In a regular week, how often does noise disturb your sleep? (1:Not at all, 2:1-2 times/week, 3:3-4 times/week, 4:5-6 times/week, 5:Every night)	83	1.35	0.88
13: Thinking about the last 12 months, when you are here at home with the windows and doors shut, how *much is your sleep disturbed by:*			
13.a. **Noise from machines or appliances inside the building**? (Refrigerator, freezer, washer, dryer, lift, AC, ventilation, water pipes, flushing toilets)	84	1.33	0.55
13.b. **Low-frequency noise** from a neighbour's sound system, TV or computer?	84	1.11	0.35
13.c. **Sound of neighbours talking**?	84	1.10	0.48
13.d. **Sound of neighbours walking**, slamming doors and dropping things, thuds from children playing?	84	1.52	0.87
13.e. **Sound of walking** in **shared** spaces of the building (staircase, hallway, etc.)?	84	1.24	0.70
13.f. **Low-frequency noise** (rumbling, muffled sound) from outside sources such as music, traffic and ventilation? (1:Not at all, 2:Slightly, 3:Moderately, 4:Very, 5:Extremely)	84	1.33	0.71
14. Age (Derived from the question "What year where you born?")	82	58	19.13
15. What is your highest completed level of education? (1:Primary school, : High school, 3:College/University)	83	2.34	0.8
16.What is your current occupation? (1:Student, 2:Stay at home, 3:On sick leave, 4:Leave of absence, 5:Unemployed, 6:Employed currently, 7:Other)	83	6.25	1.14

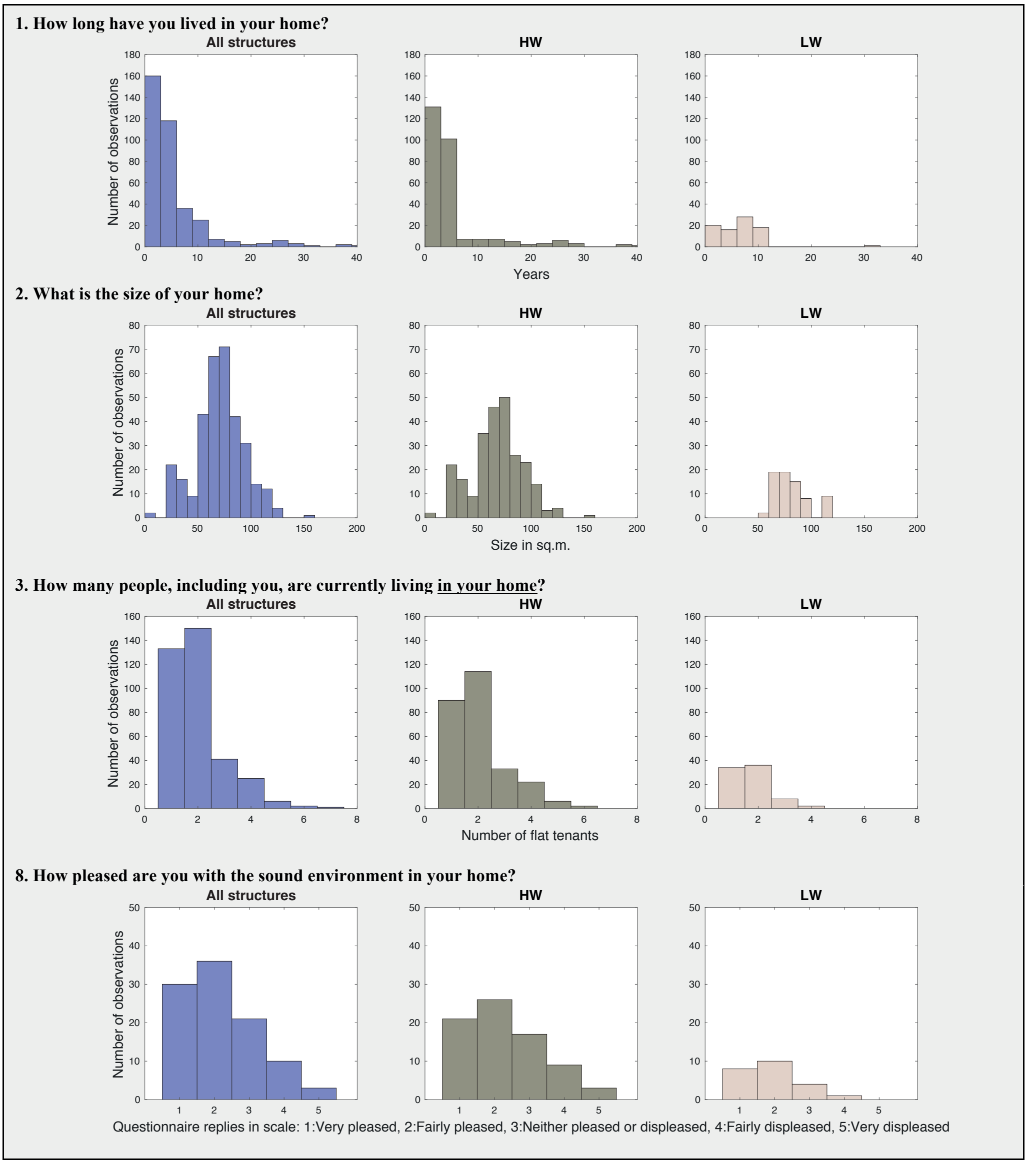


Figure 3: Questions 1-3 and 8. Histograms of questionnaire replies grouped in different structure types for the sample buildings.

Questions 6 and 7 refer to noise sources unmentioned in the questionnaire but might be of concern for the residents in the survey buildings. Specifically, 20% of HW and 22% of LW tenants have alternative sources of disturbance in question 6. Question 7 shows that 56% of those replied being somewhat or fairly annoyed. Additionally, about 30% of those commented on the nature of

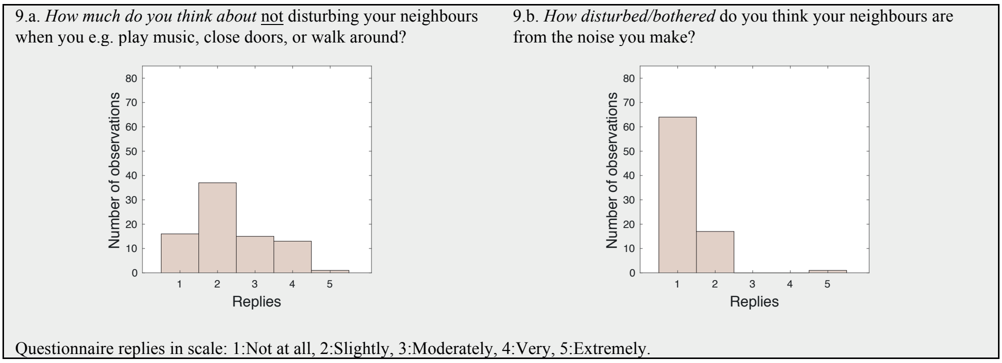


Figure 4: Questions 9.a and 9.b. Histograms of questionnaire replies for the subjects residing in wooden buildings.

the additional source: most of them referred to construction noise from building sites next to their house. That refers to a common situation in Swedish housing where new buildings are constructed or existing ones get renovated, thus there are many construction sites producing noise next to dwellings. Other additional noise types were unidentified installation noise and machinery noise (e.g. few tenants commented on some noise types that sound like washing machine or ventilation).

The satisfaction related to the acoustic living environment has been included as a variable (question 8, Figure 3) which has been used in past surveys too (Bradley 2001, Hongisto et.al. 2015). As illustrated up to 77% of subjects are very pleased or fairly pleased with their sound climate, only 11% are fairly or very displeased. For LW buildings the satisfaction ratings are even better with 80% of LW tenants being fairly or very pleased and 11% being fairly displeased.

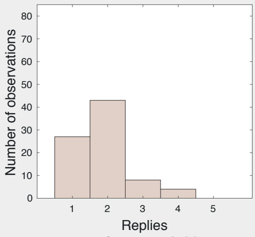
Questions 9.a and 9.b, Figure 4, are inspired by the definition of acoustic comfort provided by Rasmussen and Rindel (2010) and relate to the perception of oneself as a source of noise for others. In 9.a. tenants self-reported that they think, up to some extend, about not causing noise annoyance to their neighbors their own activities. Specifically, 47% of the total subjects replied that they think moderately, very or extremely about not disturbing their neighbors. But the LW percentage is lower at 34%; this happens probably due to increased acoustic comfort sense in wooden buildings so the residents have to think less about noise annoyance in general, both as receivers or sources of noise. Then in 9.b the majority of subjects think that their neighbors are not at all or slightly disturbed by the noise they make: this applies for 93% of the total subjects and 100% of the LW tenants.

In Figure 5 all the histograms of replies in question module 10 are presented, regarding daytime noise annoyance at home and which noise sources cause higher disturbances. The annoyance ratings were given in a Likert type 5-point-scale with the range: 1-Not at all, 2-Slightly, 3-Moderately, 4-Very, 5-Extremely. Specifically, in 10.a. it can be observed that 51% of LW tenants reported slightly annoyed by machine and installations noise (e.g. washing machine, dryer, water pipes, flushing toilets) in their flat, 33% not at all and 14% are moderately to extremely annoyed. For question 10.b. (Fig. 5) just 14% of the LW tenants are slightly disturbed by neighbors' low-frequency noise propagating through walls while only 2% are moderately to extremely annoyed.Thus, those neighbors' low-frequency noise types seem to create bigger disturbances through floors in apartments.

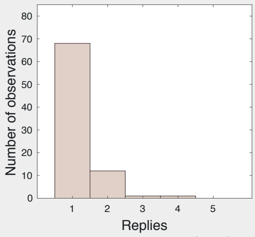
In question 10.d. (Fig. 5) it seems that 93% of LW tenants are not at all annoyed by neighbors' talking coming through walls and in 10.e. as well 81% of LW tenants replied as not at all annoyed by neighbors' airborne noise propagating through floors (9% are slightly disturbed, 5% are from

Daytime noise annoyance questions

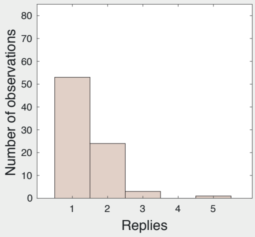
10.a. **Noise from machines or appliances inside the building**? (Refrigerator, freezer, washer, dryer, lift, AC, ventilation, water pipes, flushing toilets)



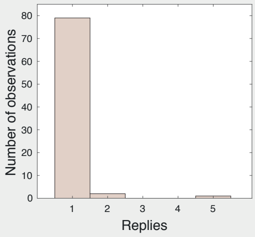
10. b. **Low-frequency noise** from a neighbour's sound system, TV or computer, coming through the walls



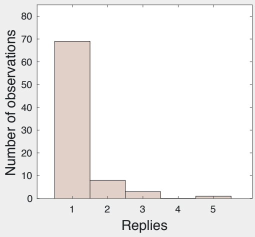
10.c. **Low-frequency noise** from a neighbour's sound system, TV or computer, coming through the floor or ceiling



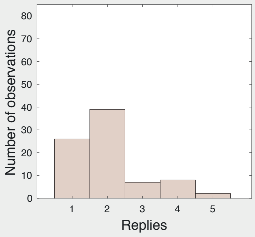
10.d. **Sound of neighbours talking,** coming through the walls



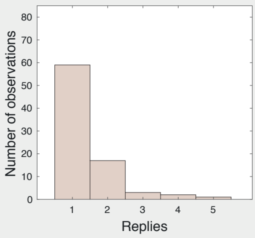
10.e. **Sound of neighbours talking,** coming through the floor or ceiling



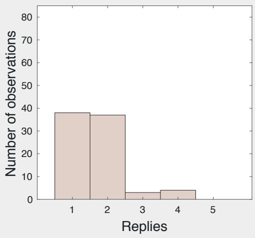
10.f. **Sound of neighbours walking**, slamming doors and dropping things, thuds from children playing, coming through the floor or ceiling



10.g. **Sound of walking** in shared spaces of the building (staircase, hallway, etc.)?



10.h. **Low-frequency noise** (rumbling, muffled sound) from **outside sources such as music, traffic and ventilation**?

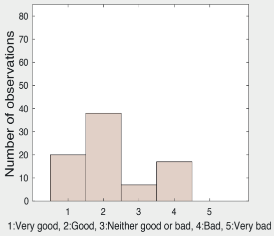


Questionnaire replies in scale: 1:Not at all, 2:Slightly, 3:Moderately, 4:Very, 5:Extremely.

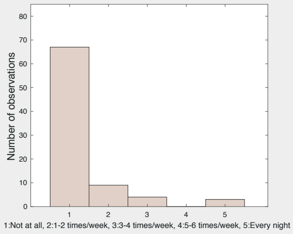
Figure 5: Daytime noise annoyance, Questions 10.a-10.h. Histograms of questionnaire replies for the subjects residing in wooden buildings.

Sleeping time noise annoyance questions

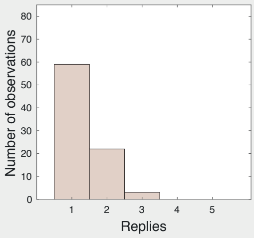
11. How would you rate your normal quality of sleep?



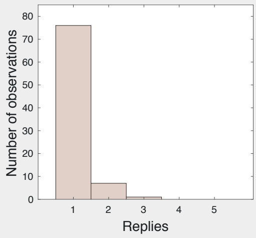
12. In a regular week, how often does noise disturb your sleep?



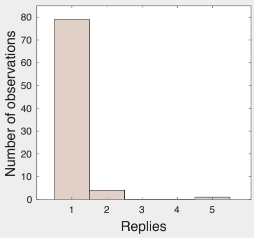
13.a. **Noise from machines or appliances inside the building**? (Refrigerator, freezer, washer, dryer, lift, AC, ventilation, water pipes, flushing toilets)



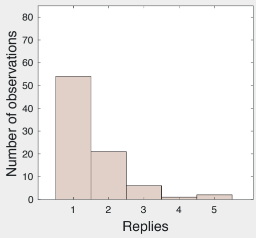
13.b. **Low-frequency noise** from a neighbour's sound system, TV or computer?



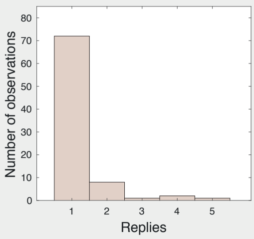
13.c. **Sound of neighbours talking**?



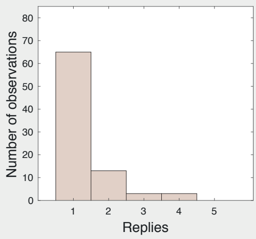
13.d. **Sound of neighbours walking**, slamming doors and dropping things, thuds from children playing?



13.e. **Sound of walking** in **shared** spaces of the building (staircase, hallway, etc.)?



13.f. **Low-frequency noise** (rumbling, muffled sound) from outside sources such as music, traffic and ventilation?



Questionnaire replies in scale: 1:Not at all, 2:Slightly, 3:Moderately, 4:Very, 5:Extremely.

Figure 6: Sleeping time noise annoyance, Questions 11-13.h. Histograms of questionnaire replies for the subjects residing in wooden buildings.

moderately to extremely annoyed). That is another indication of high acoustic comfort with sufficient airborne sound insulation in Swedish timber buildings.

For the same question of sound transmission but through floors, in 10.c, 28% of LW tenants reported slightly annoyed by neighbors' low-frequency noise propagating through floors while 5% are moderately to extremely annoyed (62% not at all).

Impact noise (stepping, kids playing, slamming doors dropping objects) propagating through floors is one of the typical disturbances in family building apartments, known by many previous studies (Vardaxis et.al.). In question 10.f. in Figure 5, the 46% of the tenants self-reported as slightly annoyed by neighbors' impact sounds while 20% report moderately to extremely annoyed. Further, in question 10.g. can be observed that 20% of LW tenants are slightly annoyed by noise in shared spaces (hallway, staircases) and 7% are moderately to extremely annoyed. Finally, 10.h. concerns outside low-frequency noise (such as traffic, music, ventilations) for which the responses suggest that 44% of LW tenants are slightly annoyed while 8% are moderately to extremely annoyed: that is another significant high response for a known noise source.

Questions 11, 12 and 13 in Figure 6 comprise the module in the questionnaire regarding noise annoyance during sleep; it includes the same questions as module question 10 without differentiation between horizontal and vertical sound transmission, i.e. from walls or floors respectively. Question 11 concerns the quality of sleep of the subjects: 20% self-report to have a bad sleep while 68% report having good or very good sleep quality. However, bad sleep quality is not necessarily connected to acoustic conditions. Then, question 12 records how often a subject is annoyed during sleep by any noise: 11% reported disturbed 1-2 times per week and 8% at least 3-4 times per week (79% not at all).

As observed by replies in question 13.a - 13.f in Figure 6, the same types of noise affect daytime and sleeping time response towards noise disturbance. Specifically, machinery/installations noise (26% slightly annoyed, 3% at least moderately-extremely annoyed) alongside neighbor's impact noise (25% reported slightly annoyed, 9% moderately-extremely) and outside low-frequency noise (15% slightly and 6% at least moderately annoyed.

Furthermore, some personal and socioeconomic data was gathered in the questionnaire as well. Regarding question 14, the distribution of age for the whole sample is close to a balance where at least 40 observations exist for every category of ages between 20-80 years old. Only subjects of age 18-85 years old were allowed to take part in the study. About 40% of the total subjects are below 40 years old, 30% are between 40-60 and 30% are older than 60. However, residents of LW buildings are older than HW buildings: specifically, 25% of LW residents are below 40 years old, 22% are between 40-60 and 53% are older than 60.

The education status of tenants was recorded too: most subjects have completed university studies (53%) in both cases of HW (54%) and LW (53%) buildings. The occupation status is the topic of question 16: most participants are in the categories of currently employed or reported "other", which mostly means pensioner as it was commented. Again it is observed the for the total sample there are 57% employed tenants and 24% pensioners while for the LW buildings there is only 43% of currently working tenants and 48% of pensioners.

Conclusions

This study presents data from a building acoustic survey in contemporary Swedish structures: the aspects of acoustic comfort in wooden buildings are in the focus of the research, as well as relevant information on lightweight (LW) family residencies in Sweden. The study sample of wooden buildings contains 7 different structures and questionnaire responses from 85 tenants. An overall level of high acoustic comfort is indicated by the self-reported data of LW tenants, with low annoyance responses and only few complaints about the acoustic environment at home.

The timber buildings of our sample were maximum 10 years old at the time of the data collection; the Swedish timber dwellings are also bigger than the average size suggested by a total research sample including many concrete structures. Additionally, most LW residents live alone or with another tenant and only 14% of them have children at home. The situation is different in concrete HW buildings, were 23% of subject have children at home and the living density is higher. Consequently, the practical conditions for LW tenants are better to ensure less noise annoyance from others inside their own flat. The self-reported satisfaction for LW buildings is very high: 80% of LW tenants being fairly or very pleased.

Summing up the noise types that cause the biggest annoyance for residents in the wooden buildings of our sample are: home machinery and installations, impact noise caused by neighbors and outside low-frequency noise; the latter concerns mostly noise sources such as road traffic (vehicle sounds), music from cars, shops, cafes, bars or outer installations such as ventilation from shops, restaurants etc. There is emphasis on the low frequency content of outside noise sounds because that can still propagate in the form vibrations inside apartments with closed windows and doors, while the middle and higher frequencies are usually filtered out from the building façade.

Additionally, if we consider that it is acceptable or at least unavoidable for some residents to be slightly annoyed by a certain noise type in their living environment then we could rank the most disturbing noise source according to the amount of subjects that self-report to be moderately, very or extremely annoyed. That would make sense since for the above three noise types the percentage of subjects reporting slightly annoyed varies between 44-51%, so there is no extreme difference in those cases for a sample of 85 subjects. Consequently, impact noise from neighbors (through floors) would be summarized as the most important noise type (20%), home installations (14%) would be the second biggest annoyance and outside low-frequency noise would come third (8%).

The questionnaire data indicates also some disturbance due to: low-frequency noise from neighbors' sound system (TV or computer) through floors or ceilings and noise in common spaces of the building (corridors, staircases). All the analyzed noise disturbances are typical noise problems in living environments (Ljungren et.al. 2014, Ljungren et.al. 2017, Vardaxis et.al. 2017). Similar responses were recorded for sleeping time noise annoyance. Most tenants did not report any sleep interruptions in Swedish wooden buildings (79%) but some reported frequent annoyance during sleep (8%). With a ranking approach as before, impact noise from neighbors (through floors) remains the most important noise type (9%), outside low-frequency noise is second highest this time (6%) and installation noise comes third (3%).

Finally, it is important to notice that in our study sample the tenants of wooden buildings are of higher age (53% older than 60) than those in typical concrete Swedish buildings; additionally, most of them are pensioners or not currently employed. Thus there is an imbalance concerning age distribution in the LW sample presented here: it might not be representative of the whole population of wooden building tenants in Sweden.

References

Boverket, Boverket´s building regulations – mandatory provisions and general recommendations, BBR, Sweden, Boverket The Swedish National Board of Housing, Building and Planning, 2016.

Bradley J.S., "Deriving acceptable values for party wall insulation from survey results", Proceeding Inter-Noise 2001, Hague, Netherlands, 2001.

EN ISO 12354 "Building Acoustics – estimation of acoustic performance of buildings from the performance of elements, – Part 1: Airborne sound insulation between rooms, – Part 2 :Impact sound insulation between rooms" (International Organization for Standardization, Geneva, Switzerland), 2017.

Hagberg K., Bard D., "Low frewquency sound transmission in multifamily wooden houses" Inter-noise 2014, Melbourne, Australia, 2014.

Hagberg K., Management of acoustics in lightweight structures, Doctoral Thesis, Engineering Acoustics, LTH, Lund University, 2018.
Hongisto V., Mäkilä M., Suokas M., Satisfaction with sound insulation in residential dwellings – The effect of wall construction, Building Environment 86, 2015, 309-320.
ISO 140 "Acoustics – Measurement of sound insulation in buildings and of building elements, – 4:Field measurements of airborne sound insulation between rooms, – 7:Field measurements of impact sound insulation of building elements" (International Organization for Standardization, Geneva, Switzerland), 1998.
ISO 15666 "Acoustics - Assessment of noise annoyance by means of social and socio-acoustic surveys" (International Organization for Standardization, Geneva, Switzerland), 2003.
ISO 16283 "Field measurement of sound insulation in buildings and of building elements, - Part 1: Airborne sound insulation, - Part 2: Impact sound insulation" (International Organization for Standardization, Geneva, Switzerland), 2014.
ISO 717 "Acoustics – Rating of sound insulation in buildings and of buildings elements. – 1:Airborne sound insulation, – 2:Impact sound insulation" (International Organization for Standardization, Geneva, Switzerland), 1996.
Ljunggren F., Simmons C., Hagberg K., "Correlation between sound insulation and occupants' perception – Proposal of alternative single number rating of impact sound", Applied Acoustics 85, 2014, 57-68.
Ljunggren F., Simmons C., Hagberg K., "Findings from the AkuLite project: Correlation between measured vibro-acoustic parameters and subjective perception in lightweight buildings" Proceedings Inter-noise 2013, Innsbruck, Austria, 2013.
Ljunggren F., Simmons C., Öqvist R., "Correlation between sound insulation and occupants' perception – Proposal of alternative single number rating of impact sound-Part II", Applied Acoustics 123, 2017.
Ljunggren F., Simmons C., Öqvist R., "Evaluation of impact sound insulation from 20Hz", Proceedings 24th International Congress on Sound and Vibration, ICSV24, London, United Kingdom, 2017.
Milford I., Høsøien C.O., Løvstad A., Rindel J. H., Klæboe R., "Socio-acoustic survey of sound quality in Dwellings in Norway", Proceedings Inter-noise 2016, Hamburg, Germany, 2016.
Negreira J., Vibroacoustic performance of wooden buildings, Doctoral Thesis, Engineering Acoustics, LTH, Lund University, 2016.
Rasmussen B., Rindel J.H., Sound insulation between dwellings - Requirements in building regulations in Europe, J. Applied Acoustics 71, 2010, 373-385.
Simmons C., Chapter 6: Developing a uniform questionnaire for socio-acoustic surveys in residential buildings. In: Building acoustics throughout Europe, Vol. 1: Towards a common framework in building acoustics throughout Europe, 2013, 102-124.
Simmons C., Hagberg K., Backman E., "Acoustical Performance of Apartment Buildings – Resident's Survey and Field Measurements", AkuLite Report 2 (2011), SP Report 58, 2011.
Simmons C., Ljunggren F., "Aku20 – Searching for optimal single number quantities in EN ISO 717-2 correlating field measurements 20-5000Hz to occupant's ratings of impact sounds – New findings for concrete floors", EuroNoise 2015, Maastricht, Netherlands, 2015.
Vardaxis N.-G., Bard D., Persson Waye K., Review of acoustic comfort evaluation in dwellings – Part I: Associations of acoustic field data to subjective responses from building surveys, Building Acoustics, 25(2), 2018, 151–170.

Paper E

Submitted to Journal of Building and Environment in June 2019.

Evaluation of noise annoyance in apartment buildings: associations of acoustic data to subjective responses.

Nikolaos-Georgios Vardaxis[1*], Delphine Bard[2]

[1] Ph.D. Candidate; nikolas.vardaxis@construction.lth.se
[2] Associate Professor; delphine.bard@construction.lth.se
* Corresponding author

Abstract: Noise can lead to serious disturbances and noise annoyance is a common issue in residential buildings. This article presents a study with focus on noise annoyance in a sample of multistory residential buildings. Acoustic data is associated to noise annoyance responses of residents gathered with a field survey. The questionnaire items, the effects from various noise sources in dwellings and from other variables on annoyance are evaluated. The research sample includes 375 observations from 34 various structure types (101 building units total). Dose-response relationships are presented for noise annoyance due to airborne and impact sound types, based on acoustic descriptors. Multiple regression models were developed with additional predictor variables such as: the size of apartment, the number of flats in the building and the presence of children at home. The frequency range of the descriptors was not found to play an important role in modeling annoyance. Specific associations of independent frequency bands to annoyance are explored too. Non-acoustic factors were analyzed as well: noise sensitivity, age, satisfaction and the structure type, concrete or wooden, were found to influence significantly the annoyance perception of apartment occupants.

Keywords: acoustic comfort, field measurements, noise annoyance, subjective responses.

---

1. Introduction

1.1. Background

Noise annoyance is a well-known problem in multistory residential buildings [1] while noise in overall can lead to serious disturbances or even health damage. For instance, environmental noise has been reported as an important risk for public health and institutions like WHO (World Health Organization) have established certain directives [2]. For indoor living environments in particular, noise can be produced by numerous sources and propagate in multiple ways [1]. The most common noise sources in housing are: installations noise (radiators, water pipes etc.), noise from neighbors in adjacent flats and staircase areas (airborne or impact sounds) and environmental noise coming from outside the buildings (crowds in busy streets or other public areas, road traffic, railways or aircraft noise) [3-10]. Boverket, the Swedish National Board of Housing, has set acoustic regulations for residencies in Sweden. In 2016 they specified a minimum weighted standardized level difference index $\boldsymbol{D_{nT,w,50}}$ of 52 dB and a maximum impact sound pressure level index $\boldsymbol{L'_{nT,w,50}}$ of 56 dB measured inside dwellings [4].

Many field surveys have been performed regarding noise annoyance in apartments, based on various noise sources, indoors or outdoors. They measured the subjective noise annoyance of residents using questionnaire surveys. They reported high correlations between the acoustic descriptors and the annoyance responses [5-12] and regression models for dose-response curves were reported. In a previous publication [3], we provided a review of acoustic surveys for noise annoyance in apartments. Noise from neighbors has been reported in previous studies as the biggest annoyance indoors, specifically impact noise types like footsteps or children playing and jumping on the floor [3, 7-12]. Similar conclusions about impact noise in flats have been reported in laboratory studies too [13, 14].

Furthermore, the acoustic descriptors with varying frequency correction spectra have been tested regarding the association to subjective annoyance [6-11]. The effect of lower frequencies on noise annoyance perception is emphasized in many studies which reported better associations of floor impact sound annoyance to $\boldsymbol{L'_{nT,w,50}}$ than to $L'_{nT,w,100}$ [7-10]. In few studies, impact sound descriptors with extended correction spectra down to 20 Hz were suggested since they were found to predict better the annoyance of the residents [7,9]. Laboratory studies tested the association of annoyance to recorded floor impact sounds confirmed the above results [15-18]. However, some of those laboratory studies concerned lightweight wooden buildings only and they reported bigger problems with low frequency behavior of lightweight floors compared to concrete ones. Those were new findings since the obligatory lower frequency limit for acoustic measurements is 100 Hz according to ISO standards [19-22]. However, 50 Hz is the officially adopted lower limit in Swedish requirements [4].

In another field survey focused on airborne sound between apartment walls, $D_{nT,w,50}$ did not improve the association to subjective annoyance while the descriptor R'_w worked better for prediction [6]. That results agree with laboratory studies which found that airborne sound descriptors which include low frequency correction spectra from 50 Hz do not correlate very well with subjective ratings [23-26].

The effects of non-acoustic factors on annoyance have also been studied in [12, 27, 28]. A wide meta-analysis concluded that demographic variables such as gender, age, income, education, occupation, home ownership and others do not affect noise annoyance significantly [27]. Similar results were reported in [12, 28]. But in the most recent study in [12] residents in their 20s self-reported higher noise annoyance and anger than other age groups. Higher noise sensitivity was correlated with increased annoyance perception and anger. Also owners of apartments expressed higher annoyance, higher anger and lower empathy than renters [12]. Noise sensitivity and personal attitudes such as fear were also found to influence annoyance in [27, 28].

1.2. Objectives

This article concerns investigation of indoor noise annoyance in a sample of Swedish (and 2 Danish) structures, most of them being contemporary apartment buildings. The overall scope of the study is to assess the perception of noise annoyance of residents in their living environment. For this reason, we examine self-reported annoyance, everyday living conditions, acoustic descriptors and building information of the test structures.

For data analysis, we combine measured acoustic data and 375 self-reported responses, after we conducted a wide survey in 34 structure types having a total of 101 building units. A questionnaire survey is presented where various noise sources and other variables are explored for their effect on residents' annoyance.

Further, we employ statistics to develop dose-response models for noise annoyance in apartments. We analyze and compare different annoyance response variables. Then we study the association of the acoustic descriptors to the responses and develop prediction models for annoyance in dwellings. We follow the typical approach, as in [5-12], of simple regression models based on acoustic descriptors. Then we test which other variables of our dataset can work additionally for multiple regression with more explanatory variables than only acoustic descriptors. Moreover, we test simple models for every measured frequency band, attempting to delve into in the effects of certain frequencies on annoyance. Additionally, the effect of several non-acoustic factors on annoyance responses is investigated.

Summing up, this manuscript provides an evaluation of self-reported annoyance in apartments and statistical modeling with dose-response curves for annoyance. The outcome adds value to measuring annoyance perception of residents and their overall acoustic comfort. Such models can be utilized as a prediction tool for acousticians, engineers and designers during planning, construction or renovation of dwellings.

2. Methods and implementation

2.1. Research design

The research sample contains 34 various structures types (32 Swedish, 2 Danish). They split into 25 heavyweight (HW) concrete structures, 7 lightweight (LW) timber structures and 2 mixed cases. Each structure corresponds to an urban block (and data block) with more than one building units, which is typical in Scandinavia.

Following the template of previous field studies [7-10], we utilized acoustic measurements compliant with the relevant ISO standards [19-22] between two same adjacent rooms, one above another. The measured test rooms are bedrooms or living rooms, typical of the building's floor plan in all cases. Thus, each structure has a representative measurement of airborne and impact sound insulation between to vertically neighboring apartments. Most acoustic data were collected from the "Green Building" database, which is an archive from a national Swedish research program about acoustic conditions in dwellings. The authors of this study performed the measurements in 3 structures. All measurements in the dataset are performed by acousticians and follow the recent ISO procedures [21, 22].

Table 1. Acoustic data summary for the sample structures.

		Impact sound index in dB		Airborne sound level difference in dB	
		$L'_{nT,w,50}$	$L'_{nT,w,100}$	$D_{nT,w,50}$	$D_{nT,w,100}$
Type:	N*	Mean (Range)		Mean (Range)	
Heavyweight (HW)	25	50.2 (40-65)	49.7 (39-64)	57.7 (44-64)	58.1 (44-65)
Lightweight (LW)	7	52.4 (49-59)	49.6 (47-54)	55.5 (48-63)	56.4 (48-65)
Mixed	2	52.1 (47-61)	51.2 (47-59)	56.9 (48-62)	56.9 (48-62)
All structures	34	50.8 (40-65)	49.7 (39-64)	57.2 (44-64)	57.7 (44-65)

* N = number of observations

Table 1 summarizes the single number quantities (SNQ) for the acoustic descriptors of the test structures. Noticeably the measurements data have a frequency range of 50-5000 Hz and the SNQs: $D_{nT,w,50}$ and $L'_{nT,w,50}$ are calculated also from 50 Hz. The building regulations in Sweden [4] demand a minimum airborne sound level difference index of $D_{nT,w,50}$=52 dB from the space outside to inside a dwelling and a maximum impact sound pressure level index of $L'_{nT,w,50}$=56 dB. However, having such strict criteria concerns only Sweden, while the official requirement of the ISO standard is 100-3150 Hz for airborne sound and 100-2500 Hz for impact sound measurements including the correction spectra C from 100Hz. Consequently, in this study we use both descriptor types for comparison, the typical indices $D_{nT,w,100}$ (= $D_{nT,w} + C_{I,100-3150}$) , $L'_{nT,w,100}$ (= $L'_{nT,w} + C_{I,100-2500}$), and the ones with extended frequency spectra and correction from 50 Hz, the $D_{nT,w,50}$ and $L'_{nT,w,50}$. The measured spectra (in one third octave bands) can be seen later in Figure 6.

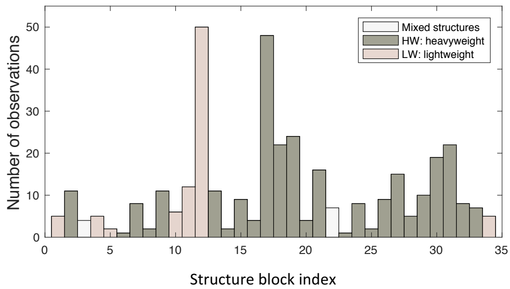
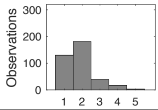
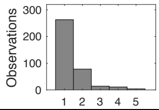
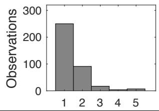
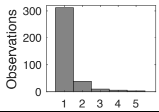
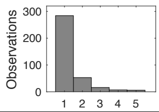
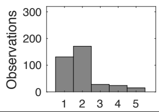
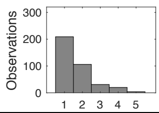
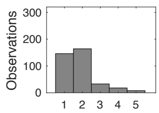


Figure 1. Histogram of the 375 replies grouped by structure blocks.

For the collection of subjective responses, a socio-acoustic survey was conducted between September 2016 - February 2018. A questionnaire was developed according to ISO 15666 [29] considering previous acoustic surveys in apartments [5-12]. The questionnaire was designed to capture annoyance by typical noise types in flats as well as other aspects of indoor acoustic comfort. Distribution was done by post mail after permission of the Research Ethics Board of Lund, Sweden. An invitation letter was sent first with the questionnaire to every test flat, then two reminder letters followed within a month. Only one questionnaire was sent to every flat: the tenant with birthday closest to 1st December was asked to fill in the survey copy. An internet link for the questionnaire was provided too. The noise annoyance questions are presented in Tables 2 and 3 (exactly as presented in the survey).

The participants of the survey provided in total 375 responses that were usable after filtering the data (initially 537 observations were collected). To fulfil the inclusion criteria, the subjects had to be between 18-85 years, to have spent at least 12 months in their flat and have normal hearing (hearing aid users were excluded). Additionally, occupants of the top floors were filtered out, since they do not have neighbors above them to make noise and their perception of noise annoyance can be different. The 375 included subjects consist of 161 men and 207 women (and 7 unreported). The total response rate was 27%, typical for such surveys [7,9]. The number of replies is among the largest. Higher sample sizes have been reported: 800 replies in [9], 702 in [8] and 600 in [5]. However, previous studies included the responses of the top floor residents and did not report much data to be filtered out.

Table 2. Question 10 data and initial statistics.

10: Thinking about the last 12 months, when you are here at home, *with the windows and doors shut, how much* disturbed are you by:	**Histogram**	**N***	**Mean**	**Std.**
10.a. **Noise from machines or appliances inside the building**? (Refrigerator, freezer, washer, dryer, lift, AC, ventilation, water pipes, flushing toilets)		370	1.87	0.84
10.b. **Low-frequency noise** from a neighbor's sound system, TV or computer, coming through the walls?		370	1.42	0.79
10.c. **Low-frequency noise** from a neighbor's sound system, TV or computer, coming through the floor or ceiling?		369	1.45	0.80
10.d. **Sound of neighbors talking,** coming through the walls?		370	1.24	0.66
10.e. **Sound of neighbors talking,** coming through the floor or ceiling?		366	1.35	0.79
10.f. **Sound of neighbors walking**, slamming doors and dropping things, thuds from children playing, coming through the floor or ceiling?		369	1.98	1.03
10.g. **Sound of walking** in shared spaces of the building (staircase, hallway, etc.)?		370	1.66	0.92
10.h. **Low-frequency noise** (rumbling, muffled sound) from **outside sources such as music, traffic and ventilation**? Scale: 1:Not at all, 2:Slightly, 3:Moderately, 4:Very, 5:Extremely		369	1.85	0.93

* N = number of observations

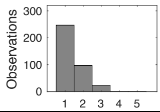
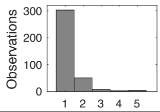
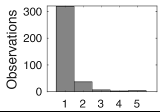
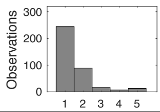
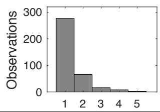
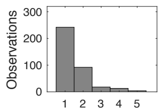
Figure 1 presents the distribution of the 375 observations in the filtered sample grouped by structure blocks. That distribution is uneven: many blocks have less than 10 observations. Then, 6 blocks have 50% of the total observations (187 out of 375). The questions analyzed in this article are presented in Tables 2 and 3, exactly as presented in the survey (translated from Swedish). Only questions 10 and 13 from the questionnaire are tabulated because they are the ones related to noise annoyance; question 10 corresponds to daytime noise annoyance (Table 2) and question 13 to annoyance during sleeping time (Table 3). The original formulations in Swedish are presented in the Appendix.

2.2. Statistical analysis

The collected data include acoustic measurements, technical variables and questionnaire responses. The aim is to test the statistical association of the variables and develop prediction models. Firstly, the consistency of the responses with scale 1-5 was tested utilizing reliability analysis. Cronbach's alpha was calculated at a value of 0.909 indicating a very high consistency for the collected responses on the examined question items [30].

To model the responses of residents, we used the acoustic descriptors as explanatory variables and explored which other variables contribute to modeling. As shown in Figure 1, the observations grouped by test structure present an uneven distribution: some building blocks have less than 10 observations while few others have up to 20 or even 50. Furthermore, the histograms and basic statistics of subjective responses in Tables 2 and 3 indicate skewed distributions. Hence, no assumption of normal distributions can be made.

Table 3. Question 13 data and initial statistics.

13: Thinking about the last 12 months, when you are here at home with windows and doors shut, how *much is your sleep disturbed by:*	Histogram	N*	Mean	Std.
13.a. **Noise from machines or appliances inside the building**? (Refrigerator, freezer, washer, dryer, lift, AC, ventilation, water pipes, flushing toilets)		370	1.41	0.65
13.b. **Low-frequency noise** from a neighbor's sound system, TV or computer?		370	1.25	0.65
13.c. **Sound of neighbors talking**?		369	1.21	0.62
13.d. **Sound of neighbors walking**, slamming doors and dropping things, thuds from children playing?		369	1.53	0.94
13.e. **Sound of walking** in **shared** spaces of the building (staircase, hallway, etc.)?		369	1.35	0.72
13.f. **Low-frequency noise** (rumbling, muffled sound) from outside sources such as music, traffic and ventilation? Scale: 1:Not at all, 2:Slightly, 3:Moderately, 4:Very, 5:Extremely		369	1.50	0.83

* N = number of observations

A non-parametric test was employed to test the effect of variables on the annoyance responses, namely the Mann-Whitney U test. This operates under the assumption of similar distributions (not normal) for ordinal independent observations [31]. The significance of differences between two sample medians is determined by the U value in the test. This is defined as:

$$U_i = n_1 n_2 + \frac{n_i(n_1+1)}{2} - \sum R_i \ ,$$

where n_i is the sample size for different groups indexed i=1 or 2. $\sum R_i$ denotes the sum of ranks of each test group. The smaller of the two values U_1 and U_2 is the final U statistic and is compared to the relevant table of predetermined critical values [31]. The reliability analysis and the U tests were performed in SPSS Statistics 24.

The questionnaire responses have a categorical scale of 1-5, which where rescaled in binary responses appropriate for binary logistic regression. Firstly, the scores of 1-5 were translated in values 0-100 following the same rule as in [28]. The formula is: $score(0-100) = 100(i - \frac{1}{2})/m$, where m denotes the number of existing categories (5 in this case) and i denotes the rank of a category. That leads to the following midpoints: 10, 30, 50, 70, 90 for m=5. Then a cutoff value of 50 was used in order to define the %A which refers to the percentage of annoyed subjects: replies of 50 and higher are classified as annoyed for the binary responses.

Binary logistic regression is applied then for the two classes: 1 as success (being annoyed) and 0 as failure. That is a non-linear regression method which uses odds to construct a linear relation and has the form of:

$$log\left(\frac{P_i}{1-P_i}\right) = b_0 + b_1 X_{1i} + b_2 X_{2i} + \cdots . + b_p X_{pi} \ ,$$

where P_i is the probability of success estimated by the model, in this case the probability of no annoyance. Then b_0, b_1,..., b_p are the estimated coefficients (b_0 being the intercept) and X_{1i} - X_{pi} are the independent variables used in the model [32]. To test if an independent variable X_{1i} has a significant effect on predicting the probability of the outcome, Wald's test and the Z value is used. Statistical significance can be proven when testing the null hypothesis H_0: $b_j=0$ against H_1: $b_j\neq 0$. When H_0 is true then:

$$Z = \frac{b_j - 0}{SE(b_j)} \approx N(0,1)$$

and if Z is large enough the H_0 is rejected at s significance level α (=0.05). For $|Z| > |\lambda_{\alpha/2}|$ the corresponding probability is derived indicating statistical significance for $p<0.05$ [32].

For nested models (i.e. models with at least one common independent variable) we can use the Deviance D for comparison, defined as:

$$D = -2lnL(b) \sim \chi^2(n-(p+1)),$$

where $L(b)$ denotes the maximum likelihood function of the coefficients matrix, n is the number of observations and $p+1$ the total parameters of the model (+1 accounts for the intercept). Thus, smaller deviance accounts for better models [32].

The model information criteria that we use for comparing non-nested models are the Akaike's information criteria (AIC) and the Bayesian information criteria (BIC), calculated as:

$$AIC(p+1) = 2(p+1) - 2lnL(b) = 2(p+1) + D \text{ and}$$
$$BIC(p+1) = (p+1)lnn - 2lnL(b) = (p+1)lnn + D.$$

Similarly to the deviance, the AIC and BIC values are based on $L(b)$ and the number of model parameters. Thus the smaller the criteria values the better. AIC usually underestimates the final values compared to BIC. For statistic entities similar to the coefficients usually reported in linear regression, the pseudo-R^2 values according to Cox-Snell and Nagelkerke are presented and defined as [32, 33]:

$$R^2_{Cox-Snell} = 1 - \left(\frac{L(b_0)}{L(b)}\right)^{2/n} \text{ with } 0 \leq R^2_{Cox-Snell} \leq 1 - \left(L(b_0)\right)^{\frac{2}{n}} \text{ and}$$
$$R^2_{Nagelkerke} = \frac{R^2_{Cox-Snell}}{1-(L(b_0))^{2/n}} \text{ with } 0 \leq R^2_{Nagelkerke} \leq 1,$$

which is more convenient to use as it can vary between 0 and 1, in the same manner as linear regression coefficients. But those pseudo coefficients do not really represent the variance explained by a model; such interpretation is valid only in linear regression. The pseudo-R^2 values serve as means of comparison between logistic regression models, in combination with the AIC/BIC values in order to compare two different models. Thus a model with high R^2 and low AIC/BIC is clearly better. Priority is put on the AIC/BIC values for model evaluation [32]. In this study we specifically use $R^2_{Nagelkerke}$ and BIC, which are easier to understand and convenient for clearer comparisons in our case. However, we present all the above model information for transparency because there is no standardized criterion [32, 33].

However, all the above criteria work for models with various predictors on the same response. To compare models concerning different responses (and predictors) one needs a different measure, which is the ROC (Receiver Operating Characteristic) curves and the corresponding AUC or AUROC (area under the ROC curve). ROC and AUC comprise a goodness-of-fit test for binary regression and represent the percentage of correctly classified observations from a model [34]. Specifically, ROC curves illustrate the sensitivity on y-axis and (1-specificity) on x-axis. Sensitivity is the proportion of true success (i.e. response of 1) classified correctly. Specificity is the proportion of true failures (i.e. 0) classified correctly as failures [32, 34]. Higher AUC values correspond to a high prediction efficiency of the tested model. An example of ROC curves and their AUC areas, is presented later in Figure 2. The probability of 0.5 (AUC of 50%), which means correct classification of outcome due to chance, is indicated with grey diagonal lines. A model has to predict better than that to be successful. Hence, AUC values above 50% are considered acceptable, above 70 % satisfactory and above 90% very good.

Finally, the regression analysis was performed using language R (version 3.3.3). The logistic regression models were developed with the glm() function. The pseudo-R^2 and BIC values were acquired by the "pscl" package functions [35]. The ROC curves and AUC values were acquired using the "pROC" package [36].

3. Results

3.1. Selection of proper response variables for subjective noise annoyance

Initially, the survey responses are investigated to see which ones can be used to represent subjective noise annoyance. Because the daytime noise annoyance module (Questions 10.a-10.h, Table 2) and the module for sleeping time (Questions 13.a-13.f, Table 3) include several questionnaire items about different types of noise stimuli. All cases of airborne and impact sound annoyance are explored, in order to associate the responses to relevant acoustic descriptors.

Table 4. AUC (or AUROC: area under the ROC curve) values used to compare goodness-of-fit for binary logistic regression models. The values of selected response models are marked by black borderlines.

Questionnaire response \ **Predictors**	$D_{nT,w,100}$	$D_{nT,w,50}$	$L'_{nT,w,100}$	$L'_{nT,w,50}$
10. Daytime noise annoyance by:				
a. Noise from machines or appliances inside the building? (Refrigerator, freezer, washer, dryer, lift, AC, ventilation, water pipes, flushing toilets)	50.6	51.8	46.7	46.7
b. Low-frequency noise from a neighbor's sound system, TV or computer, coming through the walls?	60.1	60.1	**70.3**	33.7
c. Low-frequency noise from a neighbor's sound system, TV or computer, coming through the floor or ceiling?	64.4	64.7	**71.8**	**70.1**
d. Sound of neighbors talking, coming through the walls?	**66.5**	**67.4**	**78.2**	**78.1**
e. Sound of neighbors talking, coming through the floor or ceiling?	58.8	59.4	67.9	33.9
f. Sound of neighbors walking, slamming doors and dropping things, thuds from children playing, coming through the floor or ceiling?	58.4	59.3	61.4	61.8
g. Sound of walking in shared spaces of the building (staircase, hallway, etc.)?	55.7	45.5	57.1	43.1
h. Low-frequency noise (rumbling, muffled sound) from outside sources such as music, traffic and ventilation?	53.1	53.4	64.6	45.9
13. Sleeping time noise annoyance by:				
a. Noise from machines or appliances inside the building? (Refrigerator, freezer, washer, dryer, lift, AC, ventilation, water pipes, flushing toilets)	51.3	49.3	59.0	41.4
b. Low-frequency noise from a neighbor's sound system, TV or computer?	59.8	60.5	**71.2**	**67.8**
c. Sound of neighbors talking?	**68.1**	**69.9**	**76.6**	**74.5**
d. Sound of neighbors walking, slamming doors and dropping things, thuds from children playing?	65.2	65.5	65.0	32.7
e. Sound of walking in shared spaces of the building (staircase, hallway, etc.)?	49.6	52.2	60.1	41.9
f. Low-frequency noise (rumbling, muffled sound) from outside sources such as music, traffic and ventilation?	53.0	54.6	60.9	40.2

The measurements in the dataset concern vertical airborne and impact sound transmission. We opt to match acoustic descriptors as explanatory variables to the responses selected due to statistics and semantic information, i.e. the context of every response. A simple logit model is developed for every question response and predictor variable. The AUC is utilized to compare the models since they concern different binary responses [34].

For daytime noise annoyance relevant to airborne sound, the descriptor $D_{nT,w,100}$ associates best with question item 10.d (Sound of neighbors talking, coming through the walls): 10.d shows the highest AUC value, compared to the other items in Table 4. But this descriptor concerns sound insulation in vertical direction (through floor or ceiling) not horizontally as the question suggests (through walls). Question 10.e (Sound of neighbors talking, coming through the floor or ceiling) would seem the most appropriate to associate with $D_{nT,w,100}$ in this case. On the contrary, that model has a lower AUC value of 58.8 so it associates to the descriptor worse than the

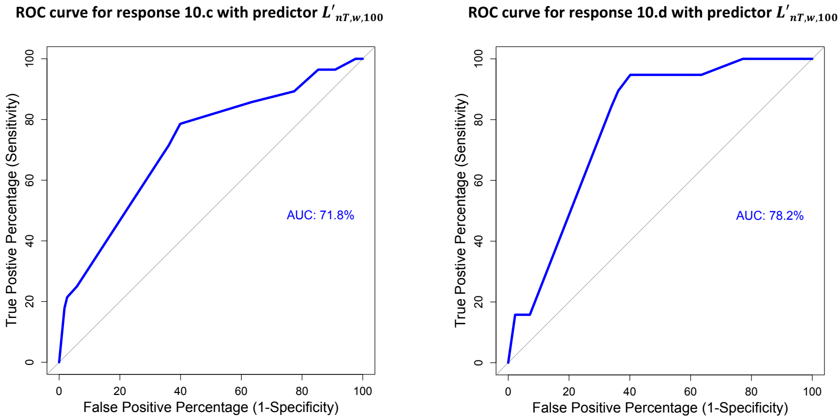


Figure 2. Examples of ROC curves for the binary logistic regression models. Grey lines represent 0.5 probability of correct classification (AUC of 50%).

response in 10.d. The exact same happens to the other airborne sound descriptor: $D_{nT,w,50}$. Hence, only the models of the descriptors $D_{nT,w,100}$ and $D_{nT,w,50}$ explain question 10.d sufficiently and they are chosen to represent the subjective daytime annoyance due to airborne sound in the study. Regarding sleeping time annoyance relevant to airborne sound, the highest AUC can be observed in Table 4 for question 13.c (Sound of neighbors talking) which refers clearly to airborne sound cases. Thus question item 13.c corresponds to sleeping time annoyance due to airborne sound.

For the case of impact noise transmission and daytime noise annoyance responses, the model with predictor $L'_{nT,w,100}$ associates best with question 10.d due to the highest AUC (Table 4). But response 10.d refers to airborne sound and was assigned to airborne sound descriptors. So considering the semantic context in this instance, the best associated impact noise question should be selected. Consequently, $L'_{nT,w,100}$ corresponds to question 10.c (Low-frequency noise coming through floors) with that model having the next highest AUC. The other descriptor $L'_{nT,w,50}$ also associates better with question 10.c in the same sense.

Explaining further, it is expected that impact sound descriptors relate to questions relevant to low frequency noise such as 10.b or 10.c (Low-frequency noise from a neighbor's sound system, TV or computer, coming through…). Or they should associate especially with item 10.f (Sound of neighbors walking, slamming doors and dropping things, thuds from children playing, coming through the floor or ceiling) which clearly targets impact noise types in apartments. Question items 10.a and 10.h could be also well associated to $L'_{nT,w,100}$ or $L'_{nT,w,50}$ since they show high mean responses for noise annoyance after item 10.f (Table 2). But this is not the case and, notably the scale replies 1 and 2 are merged together in a binary class during rescaling. So the effect of how many observations replied 2(Slightly annoyed) instead of 1(Not at all) as seen in the histograms of Table 2 is eliminated. Finally, the models explaining question 10.c are selected to represent the daytime impact noise annoyance.

For sleeping time annoyance responses due to impact sound it is observed that both $L'_{nT,w,100}$ and $L'_{nT,w,50}$ associate best with question 13.c (Sound of neighbors talking) for airborne sound (see Table 4). The same happened before for the daytime impact sound models. Again, the second best option is the model for response 10.b (Low-frequency noise from a neighbor's sound system, TV or computer?), which is the best model relevant to impact sound transmission.

3.2. Simple regression models for the subjective responses

The next step in the analysis concerns the final dose-response models based on a single predictor, specifically an acoustic descriptor which can predict best the daytime annoyance responses of the selected questions 10.c and 10.d, for the impact and airborne sound cases respectively. The same applies to the sleeping time responses 13.b and 13.c. The dataset's descriptors: $D_{nT,w,100}$, $D_{nT,w,50}$ for airborne sound reduction and $L'_{nT,w,100}$, $L'_{nT,w,50}$ for impact sound transmission, are used as independent variables to predict the percentage of annoyed residents which is indicated as %A in Figures 3-5.

3.2.1. Dose-response curves for daytime noise annoyance

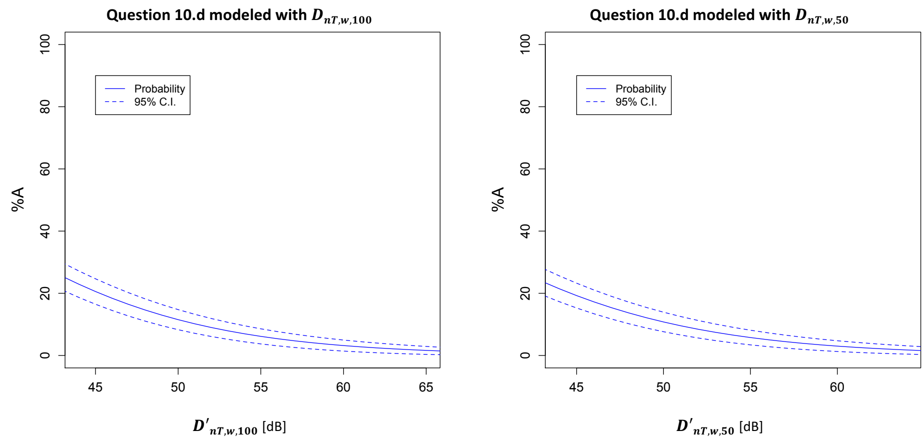


Figure 3. Dose-response curves for daytime noise annoyance due to airborne sound.

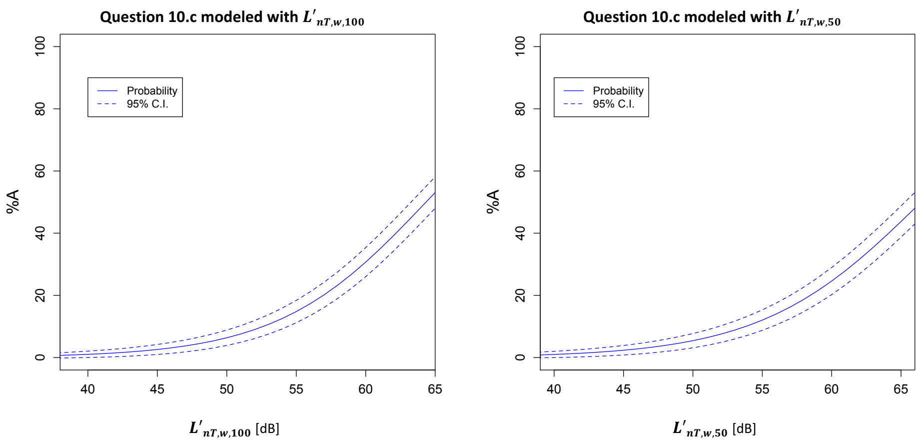


Figure 4. Dose-response curves for daytime noise annoyance due to impact sound.

A comparison of models for subjective daytime noise annoyance are presented in Table 5 and the dose-response curves in Figures 3 and 4. The model of $D_{nT,w,100}$ explaining noise annoyance due to airborne sound is the strongest: as seen in Table 5 it has the lowest BIC values (and the highest R^2) compared to the other airborne sound descriptor $D_{nT,w,50}$. Thus $D_{nT,w,100}$ predicts better the subjective responses of the airborne sound question 10.d. The numerical differences for the model parameters and criteria are very small but the selection of an ultimate descriptor still relies on the best statistics.

The details of the selected airborne sound annoyance regression model are presented in Table 6. The parameters are the intercept b_0=4.841 (p<0.1) and b_1=-0.138 (p<0.01), referring to the predictor variable $D_{nT,w,100}$.

The information criterion of interest is BIC=153.31 and the odds-ratio of $D_{nT,w,100}$ index values is 0.87 (see Exp(B) in Table 6). This means that for one more unit (dB) of airborne sound reduction the odds of annoyance decreases 13% against the odds of not being annoyed. The probabilities can be calculated from the model's dose-response curve shown in Fig.3. For an apartment of which the floor has an index of $D_{nT,w,100}$=45 dB there is a probability estimate of p=0.21 for the residents to be annoyed by sounds from neighbors (or in percentage %A=21). But for an index value of 55 dB the annoyance drops to %A=6 and for 65 dB drops to %A=2. The model parameters when using the other predictor $D_{nT,w,50}$ are very similar: b_0=4.691 (p<0.1), b_1=-0.136 (p<0.01), BIC=153.83. The dose-response curve is similar too (see Fig.3).

For daytime noise annoyance response due to impact sound, the model of $L'_{nT,w,100}$ predicting question 10.c is better (lowest BIC) compared to the model of $L'_{nT,w,50}$. Table 7 presents the details of the model summary: both parameters b_0 and b_1 are statistically significant (p<0.001), BIC=189.83. For an extra dB of $L'_{nT,w,100}$, the odds of annoyance increase circa 21% (Exp(B)=1.21). The dose-response curves (Fig. 4) suggest that in apartments with floor impact sound pressure level index of 65 dB there is a probability of p=0.53 for the occupants to be annoyed by low-frequency sounds from neighbors (%A=53). For $L'_{nT,w,100}$=55 dB the percentage %A drops to 15% and for 45 dB drops to 3%. Similar to the airborne sound cases, models based on impact sound descriptors do not differ much between them (see Table 5). Only slight effects can be seen due to descriptors with different correction spectra (100-2500Hz or 50-2500Hz) on modeling the subjective annoyance of residents. The model for $L'_{nT,w,50}$ has parameters b_0=11.5485 (p<0.001) and b_1=0.1738 (p<0.001) and BIC=191.73, very close to $L'_{nT,w,100}$.

Table 5. Model information criteria for simple regression models of daytime noise annoyance explained by acoustic descriptors.

Criteria	$D_{nT,w,100}$	$D_{nT,w,50}$	$L'_{nT,w,100}$	$L'_{nT,w,50}$
$R^2_{Nagelkerke}$	0.067	0.063	0.128	0.117
AIC	145.46	145.98	181.98	183.87
BIC	**153.31**	**153.83**	**189.84**	**191.73**

Table 6. Summary of model with $D_{nT,w,100}$ and daytime annoyance response 10.d.

Model parameters	B	S.E.	Z	P(>|Z|)	Exp(B)
b_0	4.841	2.500	1.938	0.053	
$D_{nT,w,100}$	- 0.138	0.045	-3.044	0.002	0.871
Model summary			**Model information criteria**		
D_0	D	R^2	AIC	BIC	
149.83	141.46	0.067	145.46	153.31	

Table 7. Summary of model with $L'_{nT,w,100}$ and daytime annoyance response 10.c.

Model parameters	B	S.E.	Z	P(>|Z|)	Exp(B)
b_0	-12.064	2.13	-5.656	<0.001	
$L'_{nT,w,100}$	0.188	0.04	4.609	<0.001	1.207
Model summary			**Model information criteria**		
D_0	D	R^2	AIC	BIC	
198.22	177.98	0.128	181.98	189.84	

Table 8. Model information criteria for simple regression models of sleeping time noise annoyance explained by acoustic descriptors.

Criteria	$D_{nT,w,100}$	$D_{nT,w,50}$	$L'_{nT,w,100}$	$L'_{nT,w,50}$
$R^2_{Nagelkerke}$	0.094	0.099	0.079	0.067
AIC	**113.41**	**112.86**	**126.89**	**128.28**
BIC	**121.26**	**120.71**	**134.74**	**136.14**

Table 9. Summary of model with $D_{nT,w,50}$ and sleeping time annoyance 13.c.

Model parameters	B	S.E.	Z	P(>|Z|)	Exp(B)
b_0	6.544	2.86	2.291	0.022	
$D_{nT,w,50}$	-0.176	0.05	-3.328	<0.001	0.838
Model summary			**Model information criteria**		
D_0	D	R^2	AIC	BIC	
119.07	108.86	0.099	112.86	120.71	

Table 10. Summary of model with $L'_{nT,w,100}$ and sleeping time annoyance 13.c.

Model parameters	B	S.E.	Z	P(>|Z|)	Exp(B)
b_0	-11.037	2.531	-4.360	<0.001	
$L'_{nT,w,100}$	0.156	0.048	3.243	<0.001	1.168
Model summary			**Model information criteria**		
D_0	D	R^2	AIC	BIC	
131.81	122.89	0.079	126.89	128.28	

3.2.2. Dose-response curves for sleeping time noise annoyance

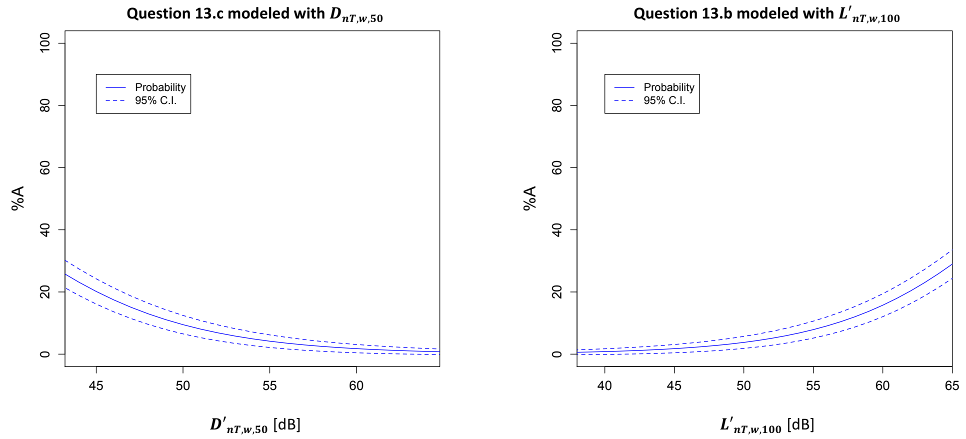


Figure 5. Dose –response curves for sleeping time noise annoyance due to airborne and impact sound.

Table 8 presents the comparison of models for annoyance during sleeping time. The model based on $L'_{nT,w,100}$ can predict sleeping time noise annoyance best (question 13.b). Then the model based on $D_{nT,w,50}$ predicting response of question 13.c has the best statistics, so those two models represent sleeping time annoyance and they are presented in Figure 5, Tables 9 and 10. The regression curves look very much like the curves for daytime noise annoyance, while the model parameters are a bit different but still very close. That can be an indication that daytime and sleeping time annoyance do not differ a lot. For 1 more dB of airborne sound reduction index $D_{nT,w,50}$ the odds for annoyance decrease by 16%. And an extra decibel of impact sound pressure levels index $L'_{nT,w,100}$ raises the odds of being annoyed by neighbors' low-frequency noise by 17%.

3.3. Multiple regression models for the subjective responses

Furthermore, additional variables are tested to be used with the acoustic descriptors in multiple regression models for prediction of the daytime noise annoyance responses. For instance, the variable $Size$ of apartment (mean 70 m^2, range 23-160 m^2) is used in the following models. Several other variables were tested as supplementary to the simple regression models, such as: duration of staying in the flat, type of house, floor (level) number, size of apartment, total number of tenants in a flat, the presence of children at home, the number of flats in the building, the number of levels (floors) in the building, the year of building construction, the type of building (lightweight, heavyweight), the type of construction frame (concrete, steel, wood), the type of floors or walls (light, heavy).

Among them, only few contributed with the airborne or impact sound descriptors in order to develop stronger models. The effect of all those variables is not negligible in the overall sense of perception. But only few worked in statistical terms for our purpose. The final models are presented below in Tables 11-15.

Table 11 presents a multivariate model with parameters: $D_{nT,w,100}$ ($p<0.01$) and $Size$ of apartment ($p<0.01$) as predictors of daytime airborne sound annoyance: question 10.d (Sound of neighbors talking, coming through the walls). The BIC is now 138.16 which is lower and indicates a stronger statistical model (it was BIC= 153.31, see Table 3). For every more dB the odds of annoyance decrease 16%, given the other variable Size remains constant. Similarly, the odds-ratio for $Size$ is 0.97, so for 1 more m^2 the odds of annoyance decrease 3%, given a constant value for $D_{nT,w,100}$. That result suggests that a bigger space at home contributes to less annoyance from neighbors' airborne noise.

The deviance test is applied also for nested models: those which have at least a common predictor, e.g. $D_{nT,w,100}$ in our case. The test calculates the difference of deviance values, which has to be bigger than $\chi^2(\nu)$ for a Chi-square distribution for ν degrees of freedom in order to reject the null hypothesis. The latter is H_0: No statistically significant difference between the two compared nested models [31]. In this case the deviance test gives $D_{before} - D_{after}$ = 127.48 – 120.38 = 7.10 > $\chi^2(1)$=6.6349 at a significance level α=0.01. Thus H_0 is rejected and the two models can be considered significantly different. Similar deviance tests can be applied successfully for each multiple model in this section.

Table 12 presents the same multiple regression model as before with one more variable $Kids$, which is a binary question item stated as: Do you have children living with you on a regular basis? (Yes/No). The same tests as before can be applied for this model to prove that the extra variable contributes to develop a stronger model. It is observed that the presence of children at home increases the odds of annoyance by 334% but this parameter is not really something that can be quantified and explained exactly like other variables.

Table 11. Summary of model with $D_{nT,w,100}$ and Size for daytime noise annoyance.

Model parameters	B	S.E.	Z	P(>|Z|)	Exp(B)
b_0	9.107	3.33	2.735	0.0062	
$D_{nT,w,100}$	-0.175	0.05	-3.345	0.0082	0.839
$Size$	-0.033	0.01	-2.590	0.0096	0.968
Model summary			**Model information criteria**		
D_0	D	R^2	AIC	BIC	
133.95	120.38	0.234	126.38	138.16	

Table 12. Summary of model with $D_{nT,w,100}$, Size and Children for daytime noise annoyance.

Model parameters	B	S.E.	Z	P(>|Z|)	Exp(B)
b_0	10.177	3.33	2.735	0.006	
$D_{nT,w,100}$	-0.198	0.05	-3.345	0.008	0.820
$Size$	-0.037	0.01	-2.590	0.010	0.964
$Kids(Yes)$	1.207	0.59	2.024	0.043	3.343
Model summary			**Model information criteria**		
D_0	D	R^2	AIC	BIC	
121.19	104.01	0.133	112.01	127.72	

Table 13. Summary of model with $D_{nT,w,100}$ and #Flats for daytime noise annoyance.

Model parameters	B	S.E.	Z	P(>|Z|)	Exp(B)
b_0	1.792	2.51	0.715	0.475	
$D_{nT,w,100}$	-0.100	0.04	-2.303	0.021	0.904
$\#Flats$	0.026	0.01	3.106	0.002	1.026
Model summary			**Model information criteria**		
D_0	D	R^2	AIC	BIC	
149.83	132.79	0.045	138.79	150.57	

Table 14. Summary of model with $D_{nT,w,100}$, #Flats and Children for daytime noise annoyance.

Model parameters	B	S.E.	Z	P(>|Z|)	Exp(B)
b_0	1.814	2.77	0.655	0.512	
$D_{nT,w,100}$	-0.109	0.05	-2.305	0.021	0.897
$\#Flats$	0.027	0.01	2.873	0.004	1.027
$Kids(Yes)$	1.146	0.55	2.085	0.037	3.146
Model summary			**Model information criteria**		
D_0	D	R^2	AIC	BIC	
136.79	116.86	0.087	124.86	140.57	

Table 15. Summary of model with $L'_{nT,w,100}$ and #Flats for daytime noise annoyance.

Model parameters	B	S.E.	Z	P(>|Z|)	Exp(B)
b_0	-10.92	2.24	-4.880	<0.001	
$L'_{nT,w,100}$	0.151	0.04	3.435	<0.001	1.163
$\#Flats$	0.019	0.01	2.661	0.0078	1.019
Model summary			**Model information criteria**		
D_0	D	R^2	AIC	BIC	
198.22	171.40	0.070	177.4	189.18	

Table 13 presents, a model with $D_{nT,w,100}$ and $\#Flats$ (number of apartments in a building) as predictor variables for question 10.d. The variable $\#Flats$ has a range of 5-113 in the dataset (Mean 28.55, Median 17) but most observations, namely 232, lie within a subrange 10-30 total flats in a sample building. That model parameters are also statistically significant for $D_{nT,w,100}$ (p<0.05) as before and $\#Flats$ (p<0.01) and BIC is now 150.57, lower and thus better than a model based on $D_{nT,w,100}$ only. The odds-ratio for $D_{nT,w,100}$ is 0.90 and for #Flats it is 1.03: the latter means for 1 more flat in a building the odds of annoyance increase by 3%. This suggests that high living density in multi-family buildings can increase noise annoyance for the residents. Additionally, as shown in Table 14 the variable $Kids$ was added to the model having a similar effect as before for the model of Table 12.

Finally, a multiple logit model for the daytime impact noise annoyance is presented in Table 15. The independent variables $L'_{nT,w,100}$ (p<0.001) and $\#Flats$ (p<0.01) are used to model annoyance of question 10.c (Low-frequency noise coming through the floor or ceiling). BIC becomes lower again and the odds-ratio for $L'_{nT,w,100}$ is 1.16, thus for 1 more dB of impact noise the odds for annoyance increase by 16% with constant number of flats. For every more apartment in a building the odds of being annoyed by neighbors' low-frequency noise increases 2%, given a constant impact sound index. For impact sound related models, no other variable was statistically significant to contribute for a multiple regression model.

Furthermore, in both cases of impact and airborne sound related multiple models a stepwise regression procedure was attempted. All examined variables were added in a model, which had no statistically significant parameters. Backwards (and forward) stepwise regression was applied in R and the end result in all cases were the same as in Tables 12 and 14. For the models of Tables 11 and 13 the modeling trials were performed manually to see if a third variable can be used for a stronger model.

3.4. Frequency band dependent models of noise annoyance responses

In this section, the effect of distinct frequency band levels on annoyance is explored. One third octave levels (in dB) from the airborne and impact sound measurements are associated to annoyance responses utilizing simple regression models. In Figure 6 the measurement curves of the sample structures are illustrated. Figure 7 presents the information criteria for models using the $D_{nT,w}$ and $L'_{nT,w}$ frequency bands as predictors of daytime annoyance responses relevant to: airborne sound 10.d (Sounds of neighbors talking, coming through the walls) and impact sound 10.c (Low-frequency noise from a neighbor's sound system, TV or computer, coming through the floor or ceiling).

For airborne sound $D_{nT,w}$, the combined low BIC and high R^2 values indicate bigger associations for the frequency bands between 400-2500 Hz (Fig. 7). The models for the bands 400-2500 Hz have also statistically significant predictor coefficients (p-values being at least p<0.05). The bands between 80-200 Hz seem to have the least association (low R^2, high BIC) to subjective responses. But there is some association for the very low frequency bands 50-63 Hz, which might suggest some effect to airborne sound annoyance. However, the BIC values are moderate and not indicate anything.

For annoyance relevant to impact sound $L'_{nT,w}$, the lowest BIC and highest R^2 values suggest that frequency band levels between 160-400 Hz are highly associated to subjective annoyance. Fairly good associations can be seen for the bands above 800 Hz, while very high associations exist also for 4 kHz and 5 kHz. The latter are neglected since the highest limit according to the ISO standards is 2500 Hz [19-22]. Those bands lie too high in the frequency spectrum to affect impact sound measurements or perception. Further, almost all narrow band levels are very significant predictors for the models (p < 0.001) except from the cases of 63 Hz, 80 Hz bands (p<0.05) and the band of 50 Hz (not significant). Overall, the lowest frequency bands (below 125 Hz) do not seem to have that high association in modeling the subjective annoyance.

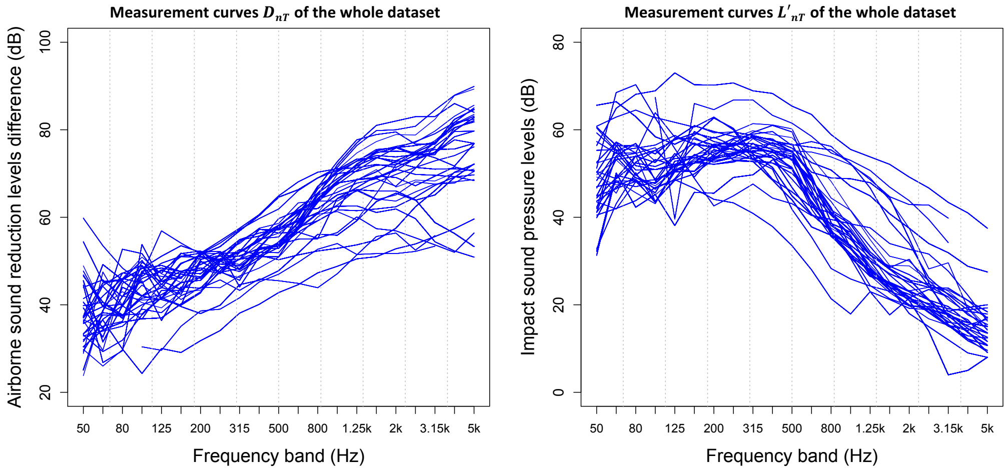


Figure 6. One third octave band curves of airborne and impact sound measurements from the dataset.

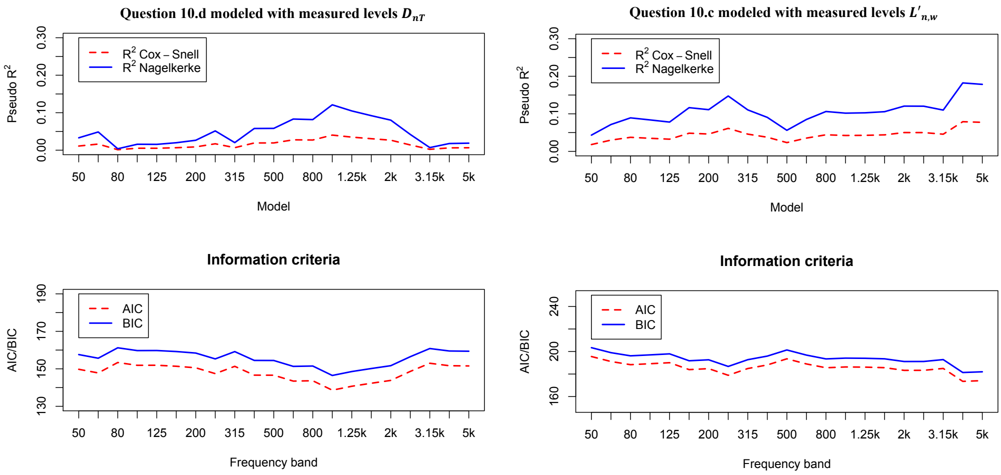


Figure 7. Narrow band regression models of airborne and impact sound descriptors for modeling the selected subjective noise annoyance responses.

3.4. Effect of non-acoustic factors on noise annoyance

In this section, non-acoustic parameters that may affect noise annoyance are investigated. Many variables were tested in the multiple regression models before as covariates, showing no significant contribution to modelling as additional predictors. However, this does not eliminate any influence on noise annoyance. In order to control for those variables, the following personal and situational parameters are explored: gender, age, sensitivity, satisfaction, occupation, income. Many of those have been analyzed in past surveys [12, 27, 28]. Additionally, the construction factors: structure type and age are investigated. Structure type has been reported to influence the acoustic behavior of the apartments and the occupants' annoyance [7,9,10,17, 37-39].

3.5.1. Control for gender and age

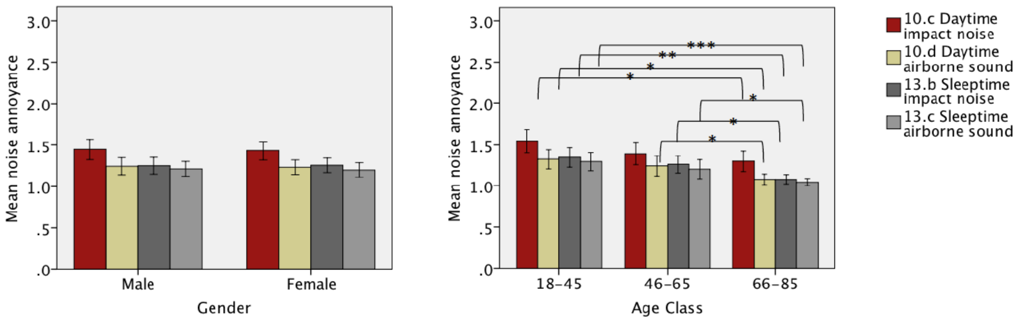


Figure 8. Mean noise annoyance comparison according to gender and age. Error-bars represent 95% C.I. (*p<0.05, **p<0.01, ***p<0.001).

There is a gender split for the subjects in this survey as 43% male and 55% female (2% unreported). Females reported slightly higher annoyance (Fig. 8). The Mann-Whitney U test indicated no statistical significance for the effect of gender on the examined responses to: daytime impact noise (Z=-0.481, p=0.631), daytime airborne sound (Z=-0.042, p=0.967) and sleeping time impact noise (Z=-0.312, p=0.755) or airborne sound (Z=-1.063, p=0.288).

To control for the variable of age, 3 different age groups were identified (Fig. 8) as: 18-45, 46-65 and 66-85 years old including 175, 101 and 92 observations respectively (7 values missing). Significant differences were found between the first and the third groups for all responses: 10.c (Z=-1.981, p=0.048), 10.d (Z=-2.541, p=0.011), 13.b (Z=-2.794, p=0.005) and 13.c (Z=-3.201, p=0.001). Significant differences were also found between the second and the third age class for cases: 10.d (Z=-1.974, p=0.048), 13.b (Z=-2.422, p=0.015) and 13.c (Z=-2.454, p=0.014).

3.5.2. Self-reported sensitivity and satisfaction

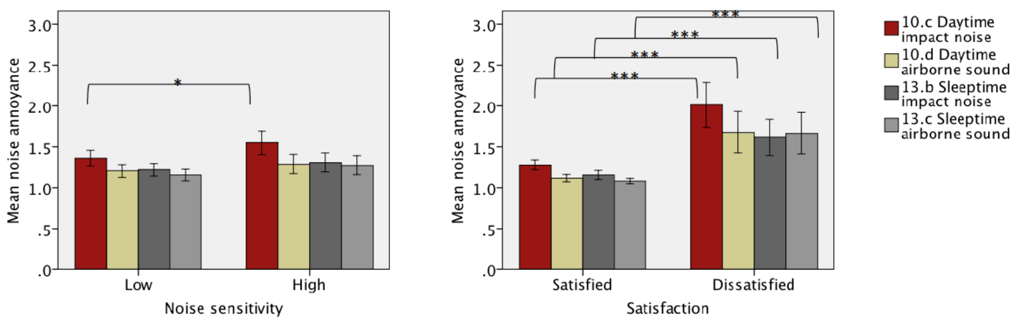


Figure 9. Mean noise annoyance comparison due to noise sensitivity and satisfaction. Error-bars represent 95% C.I. (*p<0.05, **p<0.01, ***p<0.001).

Noise sensitivity is a self-reported parameter and it has been tested as a non-acoustic factor in previous studies in relation to noise annoyance [12, 27, 28]. Two classes of low and high sensitivity (217 and 150 respectively, 8 subjects unreported) were tested following similar classification rules as for the noise annoyance. Thus replies between 3-5 (rescaled as 50, 70, 90) in a 5-point scale refer to high noise sensitivity (Fig.9). Statistical significance was indicated for the effect of noise sensitivity on the subjects' annoyance regarding only daytime impact noise (Z=-2.014, p=0.044) but not for daytime airborne sound (Z=-0.862, p=0.388) and sleeping time impact noise (Z=-1.047, p=0.295) or airborne sound (Z=-1.782, p=0.075).

The effect of satisfaction was tested on subjective annoyance. Again, two classes were assessed on a 5-point satisfaction scale as: Satisfied (replies 1-2, 288 subjects) and Dissatisfied (3-5, 79 subjects). Satisfaction affects significantly all cases of annoyance (p<0.001): 10.c (Z=-6.199), 10.d (Z=-5.905), 13.b (Z=-5.708), 13.c (Z=-

6.246). That is expected for residents not satisfied with their sound environment at home to report higher noise annoyance.

3.5.3. Other personal variables

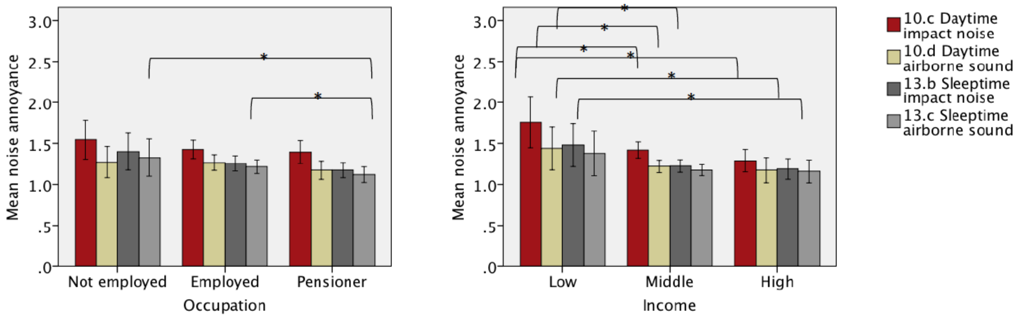


Figure 10. Mean noise annoyance comparison due to occupation and education categories. Error-bars represent 95% C.I. (*p<0.05, **p<0.01, ***p<0.001).

To control for professional status, three classes were used: not employed, employed and pensioner (or other) including 56, 201 and 111 observations respectively (7 missing). The group of not employed people includes students, unemployed persons, parents staying at home, people on parental leave or sick leave. Significant differences were found only for sleeping time airborne sound annoyance: (i) between groups 2-employed and 3-pensioners (Z=-2.041, p=0.041) and (ii) between groups 1-Not employed and 3-pensioners (Z=-2.362, p=0.018).

The effect of financial status was tested as well, using 3 categories of household income for the apartment regardless the number of tenants. A slight downward trend is shown in Figure 10, indicating that higher income categories reported less noise annoyance at home. The low income group has 51 persons with a household income below 15000 Swedish kronor (SEK) per month (circa 1500 Euro in year 2017). The high income group has 69 observations earning a household income higher than 60000 SEK per month. The middle income group (240 subjects) lies between 15k-60k SEK and 15 subjects did not report their income status. Significant differences were found between the low and middle income groups for annoyance due to: daytime impact sound (Z=-2.181, p=0.029) daytime airborne sound (Z=-2.197, p=0.028) and sleep time impact sound (Z=-2.262, p=0.024). Significant differences were also found between the low and high income groups for annoyance due to daytime impact sound (Z=-2.598, p=0.009) or airborne sound (Z=-2.458, p=0.014) and due to sleeping time impact sound (Z=-2.085, p=0.037). Overall the low income group perceives noise significantly higher than the others while no important differences were found between the middle and high income groups.

3.5.4. Construction variables

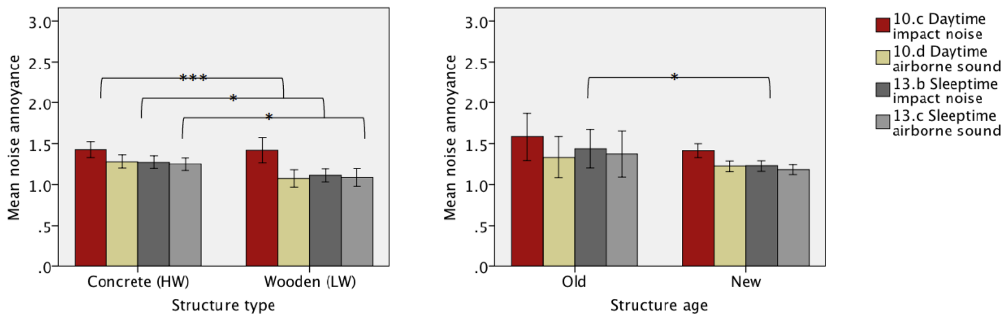


Figure 11. Mean noise annoyance comparison due to structure type and structure's age. Error-bars represent 95% C.I. (*p<0.05, **p<0.01, ***p<0.001).

The effect of structure type (HW: heavyweight, LW: lightweight) on subjective annoyance was tested for the 25 HW and 7 LW structures, neglecting the 2 mixed structures. It was found statistically significant for annoyance relevant to: daytime airborne sound (Z=-3.255, p=0.001), sleep time impact sound (Z=-2.187, p=0.029) and sleep time airborne sound (Z=-2.485, p=0.013). There was no significance for daytime impact noise annoyance (Z=-0.379, p=0.705), which is surprising since impact noise is the highest reported noise type [1,3,7-10].

The effect of structure's age was tested as well, so contemporary structures built within the decade 2007-2017 comprised the category of new structures while every structure built before 2007 was in a class of old ones (Fig. 11). The structures split into 5 old and 29 new ones, with 49 and 326 observations respectively. No significant differences were found between the two classes, except only for sleeping time impact noise annoyance (Z=-2.667, p=0.008). However, it could be expected for older structures to have a negative effect on annoyance but this hypothesis was not supported.

4. Discussion

Initially, an evaluation of noise annoyance can be done directly from the survey replies. As can be seen in Table 2, impact sounds from neighbors (response 10.f) is the most disturbing noise type in the sample structures. Installations noise was recorded as the second most disturbing source (10.a: machinery, appliances, ventilation etc.). Then low-frequency noise from outside the building (10.h) comes third and noise in the common areas (staircase, elevators) comes fourth. The least annoyance was reported due to airborne sound from neighbors (10.d, 10.e) which is expected. Impact sound has been much reported as the biggest disturbance in apartments [1,3,7-10].

The questionnaire responses are associated to acoustic descriptors in order to establish dose-response models. However, some models have insufficient AUC values (Table 4). For instance, question 10.f regarding annoyance from neighbors' impact sounds ("… walking, slamming doors and dropping things…") associates weakly with the relevant impact sound pressure level index $L'_{nT,w,100}$. Among the 3 impact sound related questions 10.b, 10.c and 10.f, the latter seems to be less associated with the impact sound descriptors (lowest AUC). This is noteworthy since that question was designed to refer to the most usual cases of impact noise in living environments but evidently failed to represent impact sound annoyance. Another interesting result is that the model of response to question 10.b has similar results to 10.c, while they refer to low-frequency neighbors' noise through walls and through floors respectively.

However, question 10.c ("low-frequency noise from neighbors… through floor or ceiling") associates best to $L'_{nT,w,100}$, thus it is used for modelling to establish a dose-response relationship. There is no clear evidence why this happens in the survey responses. Similar questions have been used quite successfully in previous studies [6-10], e.g. for noise annoyance by neighbors' impact sound such as footsteps. A possible explanation can be limited knowledge of residents regarding the type of noise, especially for sound dominated by low frequencies such as impact noise or bass sounds. Maybe residents cannot distinguish such noise types or there may not be considerable issues with noise since the floor insulation of the structures is generally sufficient. Most structures of the study comply with the Swedish regulations [4] imposing a maximum impact sound index value of $L'_{nT,w,50}$=56 dB.

Question 10.d ("Sound of neighbors talking through the walls") associates best with all acoustic descriptors, airborne or impact sound related, while question 10.e ("Sound of neighbors talking through the floor or ceiling") associated with worse AUC values (Table 4). This may again be related to good floor insulation conditions or directivity misconceptions of occupants. It is also important that the airborne sound related models had AUC lower than 70%, meaning lower strength for the prediction ability of the models. Specifically, for simple models based on $L'_{nT,w,100}$, the one for 10.d has AUC=66.5 and for 10.e has a much lower AUC=58.8. For that reason, the strongest model was opted using response 10.d even if the question formulation refers to sounds through walls.

Furthermore, the difference between response models for questions of low-frequency sounds through walls and through floors or ceiling (items 10.b and 10.c respectively) is very small. All the above cases (10.b-10.e) may indicate some issues of understanding sound directivity. Perception of noise directivity might be distorted inside an apartment, since sound propagation in buildings depends on the structure connections and complex phenomena like indirect propagation through walls, known as flanking transmission [7, 39, 40]. This is indirect transmission of sound via surfaces connected to the surface of direct propagation: e.g. impact sound can travel directly through a floor and cause flanking transmission through walls, which is a usual problem in multistory buildings.

4.1 Assessment of simple dose-response models

The presented dose-response curves (Fig. 3-5) are derived from simple regression models having with acoustic descriptors as predictors. Similar curves were presented in [8]. Comparing the associations of airborne and impact sound descriptors to subjective annoyance during daytime (chapter 3.2.1), a bigger effect is observed for impact sound in the models. Firstly, it can be seen in the dose-response curves: the ones based on impact sound are steeper than those for airborne sound (Fig. 3, 4). This also means that the probability of being annoyed changes faster with one more dB of impact sound compared to the airborne sound cases. Secondly, it is reflected in the odd-ratios: 1 more dB of airborne sound reduction index affects the odds of annoyance by 15% decrease while 1 more dB of impact sound index raises the odds of annoyance by 21%. The same applies to the sleeping time annoyance models: odds ratios indicate 16% decrease and 17% increase due to $D_{nT,w,100}$ and $L'_{nT,w,100}$ respectively.

Furthermore, the chosen models for impact sound were stronger than airborne sound cases in terms of statistics. They have higher AUC values (Table 4) and higher statistical significance for their model parameters ($p<0.001$, Tables 6,7). That data indicates higher ability to predict the response of the model.

All the above suggest that the effects of impact sound are stronger for noise annoyance in flats. Additionally, noise types relevant to impact sound were reported as the most disturbing in this study, like in other surveys, highlighting the importance of impact noise types and impact sound pressure level index as predictor of subjective annoyance. This deduction comes in agreement with the conclusions of previous studies, which report impact noise types as the most critical factor of noise annoyance for tenants in apartments [1,3,7-10].

4.2 Effects of certain frequencies

The difference between the examined airborne sound descriptors $D_{nT,w,100}$ and $D_{nT,w,50}$ were really small in modeling and the same applies for impact sound descriptors $L'_{nT,w,100}$ and $L'_{nT,w,50}$. The descriptors from 100 Hz were associated best in all modelling cases except for the airborne sound related annoyance during sleep. Those findings disagree with studies which reported that impact sound descriptors with extended low-frequency correction spectra down to 50 Hz (or 20 Hz in some cases) are essential to model subjective annoyance in lightweight buildings [7,9,17, 18, 37-39]. Those studies tested the descriptors including frequency bands below 100 Hz such as $L'_{nT,w,50}$ or $L'_{nT,w,20}$ and they were found to be better correlated to subjective noise annoyance responses. Some studies [7,9,10, 17, 18, 39] were focused on LW wooden structures which were reported to have a different acoustic behavior than typical HW concrete structures, especially in the low frequency range. However, the sample of this study is dominated by **concrete structures**, namely including 25 HW, 7 LW and 2 mixed structures. In [9] it is also observed that low-frequency inclusion for descriptors affects highly the association of annoyance to LW structures but not to the HW ones.

Individual frequency bands were also tested as predictors to explore frequency specific effects on annoyance. For airborne sound annoyance, the bands between 400-2500 Hz were found to have significant effects (Fig. 7). The strongest models seem to be for bands of 630-2000 Hz indicating the biggest influence at that range. Low frequency bands below 200 Hz had generally low associations. Similar results were reported in laboratory studies where airborne sound descriptors including lower frequencies did not associate well to subjective loudness [23, 24]. Specifically, the standardized $D_{nT,w,100}$ was found higher correlated to subjective loudness than $D_{nT,w,50}$.

For impact sound related annoyance and the measured spectra, the bands between 160-400 Hz show the strongest association (Fig. 7). Bands above 800 Hz associate well too but the bands below 125 Hz do not associate that well. This appears again inconsistent with past studies supporting that frequency bands down to 50 Hz (or even 20 Hz) should be included in the evaluation of impact sound and the prediction of subjective noise annoyance [7, 9, 17, 18]. It is highlighted again that those studies focus on lightweight structures while this study includes **74% concrete structures** in the survey sample. However, other studies included both HW and LW structures concluding again that descriptors including low frequencies work better for prediction of subjective annoyance: $L'_{nT,w,50}$ was suggested in [8] and $L'_{nT,w,20}$ in [9, 17, 18]. Overall, most of the latest studies support the inclusion of low frequencies [3, 7-10, 17, 18].

4.3 Multiple regression models

Supplementary variables can contribute to modeling subjective noise annoyance besides the acoustic descriptors. The models become stronger than the simple regression cases when adding certain variables, such as the size of apartment for the airborne sound models. It is observed that bigger apartments are related to lower noise annoyance due to airborne sound. However, the variable $Size$ was not significantly associated with the impact sound related models. This probably relates to impact sound propagation which happens easier within a building structure and a bigger space inside a flat does not prevent that sufficiently.

The number of apartments in a building also plays a role in annoyance perception. The variable $\#Flats$ associated well in both airborne and impact sound annoyance modeling. The overall effect was slight but still it demonstrates that living density matters: for every more apartment in a block of flats the odds of annoyance due to neighbors' noise increase 3% for airborne sound and 2% for impact sound. Additionally, a third variable was used in the multivariate models for airborne sound cases, namely the presence of children at home. The odds of annoyance increase dramatically if there are children at home according to the models (more than 300%). However, a quantitative interpretation is probably careless in this case.

4.4. Effect of non-acoustic factors on noise annoyance

The effect of non-acoustic factors was investigated as well. The variables of gender and age were controlled. No significant differences were found due to gender but the opposite happens for age: residents older than 65 years reported significantly lower annoyance in overall. Similar findings appeared in [12]: Gender had no effect but relatively young or old persons perceived lower noise annoyance.

Noise sensitivity and satisfaction were found to have an effect, which is expected. Higher noise sensitivity or lower satisfaction leads to higher noise annoyance perception according to the findings (Fig.9). Similar effects of noise sensitivity on annoyance has been presented in field acoustic studies [12, 27, 28] and satisfaction has been tested too [6].

Few significant differences were found due occupation status and income. Residents classified as not employed (unemployed, students or currently not working) reported higher noise annoyance than employed or pensioners. Additionally, the low income class was found to report significantly higher noise annoyance than others. Previous meta-analyses of various annoyance surveys have demonstrated that the effects of demographic variables are not so important on annoyance [27, 28].

Finally, the type of structure and age of structure were explored: the type of structure plays an important role on noise annoyance but not the age as indicated by the results. The difference between HW and LW is highlighted again in this study as it was highlighted in previous field studies and laboratory experiments [3, 7-10, 17, 18].

4.5 Limitations of the study

There are limitations for the models and the dose-response curves presented in this study (Fig. 3-5, Tables 5-15). The observed $D_{nT,w,100}$ and $D_{nT,w,50}$ values vary between 44-65 dB, which means that the airborne sound based regression models should be considered valid only within that range descriptor values. The same applies to the impact sound related models because the descriptors $L'_{nT,w,100}$ and $L'_{nT,w,50}$ have a range between 39-65 dB.

Limitations also exist due to sample size. The acoustic data were acquired from the Swedish Green Building database with most structures complying to minimum criteria according to the regulations stated in [4]. Hence the conditions of the acoustic environment in the Swedish dwellings of this study are very satisfactory in general. This partially explains why the overall annoyance responses are quite low and residents did not report that highly annoyed in the study. Of course, the results of this study deduce a positive evaluation for the contemporary Swedish dwellings. However, the sample data are possibly biased towards positive evaluation and the annoyance results are probably not representative of the whole Swedish population. Further, the distribution of observations per structure block are uneven thus the studied structures were not represented equally in the dataset.

Last but not least, the presented study includes 25 HW concrete, 7 LW wooden and 2 mixed structures. The total sample is clearly dominated by concrete buildings, thus comparison of the results with studies based on different structures should be very done carefully. Especially when discussing which acoustic descriptors associate better to noise annoyance (with lower frequencies or not), it is important to clarify which type of structures are investigated. The differences in acoustic behavior between HW and LW have been repeatedly reported as significant in past studies [3, 7-10, 17, 18].

5. Conclusions

An assessment of noise annoyance in 34 different structures takes place and various models are presented for the prediction of self-reported noise annoyance in apartment buildings. The questionnaire responses from a survey are evaluated by simple regression models and their information criteria. Some responses did not associate well with acoustic descriptors although they were designed verbally to target typical noise types in residential buildings.

Noise annoyance from neighbors' impact sounds was reported as the highest disturbance in the survey. Then noise from installations inside the building (ventilation, etc.) comes second and noise from low-frequency noise outside the building comes third in the residents' replies.

The daytime airborne and impact sound related annoyance were analyzed individually. Two different question responses were associated to airborne and impact sound descriptors: one considering airborne and the other impact noise annoyance. The dose-response models for impact sound were statistically more significant and stronger than airborne sound models. The effects of impact sound on noise annoyance are bigger in the dose-response curves too. All the above agree with past studies which report that impact noise in dwellings have the greatest role in the annoyance perception of residents.

Multiple regression models were developed too with building data as predictor variables additional to acoustic descriptors, namely: the size of apartment and the total number of flats in the building. A larger apartment can lead to less airborne sound annoyance from neighbors. Additionally, more flats in a building increase the odds of annoyance due to noise from neighbors. The presence of children at home was tested as well and was found to have a drastic effect on annoyance. More variables were tested but did not contribute to dose-response models.

Non-acoustic factors were investigated too. Gender had no effect on noise annoyance but age did: older residents were less annoyed. Significant effects were found also for noise sensitivity, satisfaction and structure type. Some effects were found due to occupation and income status too.

The effect of acoustic descriptors with different frequency range to annoyance was found negligible in this study, for both cases of airborne sound and impact sound. The relevant descriptors $D_{nT,w,100}$, $D_{nT,w,50}$ for airborne sound and $L'_{nT,w,100}$, $L'_{nT,w,50}$ for impact sound were used to predict the residents' annoyance with very slight differences in the end. This contradicts with previous findings indicating that correction spectra with lower frequencies are necessary for the prediction of annoyance related to impact sound but also airborne sound in few cases. However, most of those studies concern lightweight structures while this survey's results come from a dataset dominated by typical concrete structures, namely 25 out of 34.

Further, the building data includes certified buildings for sufficient acoustic conditions. That fact might affect our results introducing bias towards the overall self-reported noise annoyance from the tenants. It could probably affect the associations of acoustic descriptors to subjective response as well.

Acknowledgements

This article was written within the doctoral research project "Acoustic Comfort in Apartment Buildings" funded by Saint-Gobain Weber.

Appendix A

Table A1. Question 10 presented in the Swedish formulation.

10. Följande frågor rör specifika ljudkällor som kan höras i bostaden. När du tänker på *de senaste 12 månaderna*, när *du är hemma i din bostad med fönster och dörrar stängda* hur <u>störd</u> är du av:
10.a. **Buller från maskiner eller tekniska installationer i byggnaden** (kyl/frys, tvättmaskiner, torktumlare, hiss, luftkonditionering, ventilation, vattenledningar, spolande toaletter)
10.b. **Lågfrekvent buller** (basljud) från grannars musikanläggning, TV eller datorer som hörs <u>genom väggen</u>?
10.c. **Lågfrekvent buller** (basljud) från grannars musikanläggning, TV eller datorer som hörs <u>genom golvet eller taket</u>?
10.d. **Grannars prat** som hörs <u>genom väggen</u>?
10.e. **Grannars prat** som hörs <u>genom golvet eller taket</u>?
10.f. **Ljud från grannars steg**, smällande i dörrar, saker som tappas i golvet, dunsar från lekande barn som hörs <u>genom golvet eller taket</u>?
10.g. **Ljud från steg** från gemensamma utrymmen (trappuppgång, korridor etc) i huset?
10.h. **Lågfrekvent buller** (mullrande, dovt ljud) från ljudkällor **utomhus som musik, trafik och ventilation?** Scale: 1: Inte alls, 2:Något, 3:Ganska mycket, 4:Mycket, 5:Oerhört

Table A2. Question 13 presented in the Swedish formulation

13. När du tänker på de senaste 12 månaderna, när du är hemma (med fönster och dörrar stängda) hur *mycket störs din sömn av:*
13.a. **Buller från maskiner eller tekniska installationer i byggnaden** (kyl/frys, tvättmaskiner, torktumlare, hiss, luftkonditionering, ventilation, vattenledningar, spolande toaletter)
13.b. **Lågfrekvent buller** (basljud) från grannars musikanläggning, TV eller datorer?
13.c. **Grannars prat**?
13.d. **Ljud från grannars steg**, smällande i dörrar, saker som tappas i golvet, dunsar från lekande barn?
13.e. **Ljud från steg** från **gemensamma** utrymmen (trappuppgång, korridor etc) i huset?
13.f. **Lågfrekvent buller** (mullrande, dovt ljud) från ljudkällor utomhus som musik, trafik och ventilation? Scale: 1: Inte alls, 2:Något, 3:Ganska mycket, 4:Mycket, 5:Oerhört

References

1. Rasmussen B., Rindel J.H., Sound insulation between dwellings - Requirements in building regulations in Europe, J. Applied Acoustics 71, 2010, 373-385.
2. WHO, Environmental noise guidelines for the European region, World Health Organization (WHO), Regional Office for Europe, 2018.
3. Vardaxis N.-G., Bard D., Persson Waye K., "Review of acoustic comfort evaluation in dwellings – Part I: Associations of acoustic field data to subjective responses from building surveys", Building Acoustics, 25(2), 2018, 151–170.
4. Boverket, Boverket´s building regulations – mandatory provisions and general recommendations, BBR, Sweden, Boverket The Swedish National Board of Housing, Building and Planning, 2016.
5. Bradley J.S., "Deriving acceptable values for party wall insulation from survey results", Proceeding Inter-Noise 2001, Hague, Netherlands, 2001.
6. Hongisto V., Mäkilä M., Suokas M., Satisfaction with sound insulation in residential dwellings – The effect of wall construction, Building Environment 86, 2015, 309-320.
7. Ljunggren F., Simmons C., Hagberg K., "Correlation between sound insulation and occupants' perception – Proposal of alternative single number rating of impact sound", Applied Acoustics 85, 2014, 57-68.
8. Milford I., Høsøien C.O., Løvstad A., Rindel J. H., Klæboe R., "Socio-acoustic survey of sound quality in Dwellings in Norway", Proceedings Inter-noise 2016, Hamburg, Germany, 2016.
9. Ljunggren F., Simmons C., Öqvist R., "Correlation between sound insulation and occupants' perception – Proposal of alternative single number rating of impact sound-Part II", Applied Acoustics 123, 2017, 143-151.
10. Hagberg K., Bard D., "Low frequency sound transmission in multifamily wooden houses" Inter-noise 2014, Melbourne, Australia, 2014.
11. Bodlund K., Alternative reference curves for evaluation of the impact sound insulation between dwellings, J. Sound and Vibration 102, 381-402 (1985).
12. Park S. H., Lee P. J., Reaction to floor impact noise in multi-storey residential buildings: The effects of acoustic and non-acoustic factors. Applied Acoustics 2019 (150): 268–278.
13. Jeon J. Y., Lee P. J., Kim J. H., Yoo S. Y., Subjective evaluation of heavy-weight floor impact sounds in relation to spatial characteristics, J. Acoust. Soc. Am. 2009, 125(5): 2987-94.
14. Jeon J. Y., Lee P. J., Sato S., Use of standard rubber ball as an impact source with heavyweight concrete floors. J. Acoust. Soc. Am. 2009, 126, 167-178.
15. Kylliäinen M., Hongisto V., Oliva D., Rekola L., A laboratory listening experiment on subjective and objective rating of impact sound insulation of concrete floors, Proceedings Inter-Noise 2016, Hamburg, Germany, 2016.
16. Kylliäinen M., Hongisto V., Oliva D., Rekola L., Subjective and Objective Rating of Impact Sound Insulation of a Concrete Floor with Various Coverings, Acta Acustica united with Acustica, 2017, 103:236-250.
17. R. Öqvist, F. Ljunggren, R. Johnsson, Listening test of walking noise from 20 Hz in dwellings, Proceedings Inter-noise 2017, 3935-3942, Hong Kong, China, 2017.

18. Späh, M., Hagberg, K., Bartlomé, O., Weber, L., Leistner, P., Liebl, A., Subjective and Objective Evaluation of Impact Noise Sources in Wooden Buildings, Building Acoustics 2013, 20(3): 193-214.
19. ISO 140 "Acoustics – Measurement of sound insulation in buildings and of building elements, – 4: Field measurements of airborne sound insulation between rooms, – 7: Field measurements of impact sound insulation of building elements" (International Organization for Standardization, Geneva, Switzerland), 1998.
20. ISO 717 "Acoustics – Rating of sound insulation in buildings and of buildings elements. – 1: Airborne sound insulation, – 2: Impact sound insulation" (International Organization for Standardization, Geneva, Switzerland), 1996.
21. ISO 16283 "Field measurement of sound insulation in buildings and of building elements, - Part 1: Airborne sound insulation, - Part 2: Impact sound insulation" (International Organization for Standardization, Geneva, Switzerland), 2014.
22. EN ISO 12354 "Building Acoustics – estimation of acoustic performance of buildings from the performance of elements, – Part 1: Airborne sound insulation between rooms, – Part 2: Impact sound insulation between rooms" (International Organization for Standardization, Geneva, Switzerland), 2017.
23. Monteiro C., Machimbarrena M., De la Prida D., "Subjective and objective acoustic performance ranking of heavy and light weight walls". Applied Acoustics 2016, (110) 268–279.
24. Rychtáriková M., Muellner H., Chmelík V., Roozen N. B., Urbán D., Garcia, D. P., Glorieux C., Perceived Loudness of Neighbour Sounds Heard Through Heavy and Light-Weight Walls with Equal R_w+ C_(50-5000), Acta Acustica united with Acoustica 2016, (102:1) 58-66.
25. Hongisto V., Oliva D., Keränen J., Subjective and Objective Rating of Airborne Sound Insulation – Living Sounds, Acta Acustica united with Acustica, 2014, 100: 848-864.
26. Virjonen P., Hongisto V., Oliva D., Optimized single-number quantity for rating the airborne sound insulation of constructions: Living sounds, J. Acoust. Soc. Am., 2016, 140(6): 4428-4436.
27. Fields J.M., Effect of personal and situational variables on noise annoyance in residential areas. J. Acoust. Soc. Am. (1993) 93:2753-63, 1993.
28. Miedema H. M. E., Vos H., Demographic and attitudinal factors that modify annoyance from transportation noise, J. Acoust. Soc. Am. (1999) 105(6):3336-3344, 1999.
29. ISO 15666 "Acoustics - Assessment of noise annoyance by means of social and socio-acoustic surveys" (International Organization for Standardization, Geneva, Switzerland), 2003.
30. Tavakov M., Dennick R., Making sense of Cronbach's alpha, International Journal of Medical Education 2011;2:53-55, 2011.
31. Sheskin D.J., Handbook of Parametric and Nonparametric Statistical Procedures, 2nd Edition, CRC Press, 2000.
32. Agresti A., An Introduction to Categorical Data Analysis, 2nd Edition, Wiley, 2007.
33. Nagelkerke N. J. D., "A Note on a General Definition of the Coefficient of Determination", Biometrika 78(3). 1991, 691-692.
34. Huber-Carol C., Balakrishnan N., Nikulin M., Mesbah M., Goodness-of-Fit Tests and Model Validity, Springer, 2002.
35. Jackman S., pscl: Classes and methods for R. Developed in the Political Science Computational Laboratory, Stanford University. Department of Political Science, Stanford University, Stanford, CA. R package version 1.03. 5
36. Robin X., Turck N., Hainard A., Tiberti N., Lisacek F., Sanchez J.-C., Müller M., pROC: an open-source package for R and S+ to analyze and compare ROC curves, BMC Bioinformatics 7:77, 2011.
37. Hagberg K., Management of acoustics in lightweight structures, Doctoral Thesis, Engineering Acoustics, LTH, Lund University, 2018.
38. Ljunggren F., Simmons C., Öqvist R., "Evaluation of impact sound insulation from 20Hz", Proceedings 24th International Congress on Sound and Vibration, ICSV24, London, United Kingdom, 2017.
39. Negreira J., Vibroacoustic performance of wooden buildings, Doctoral Thesis, Engineering Acoustics, LTH, Lund University, 2016.
40. Vigran T.E., Building Acoustics, CRC Press, 2008.

Paper F

PROCEEDINGS of the
23rd International Congress on Acoustics

9 to 13 September 2019 in Aachen, Germany

Acoustic comfort assessment in heavyweight residential buildings: acoustic data associated to subjective responses.

Nikolaos Georgios VARDAXIS[1]; Delphine BARD[2]

[1] Lund University, LTH, Sweden

[2] Saint-Gobain Nordic & Baltic Delegation, Denmark / Lund University, LTH, Sweden

ABSTRACT

This article presents a study aiming to explore and evaluate acoustic comfort in residential multistory buildings in Sweden. Acoustic data was associated to self-reported responses acquired by a survey: a questionnaire was setup researching the response to noise annoyance from multiple sources in a flat and the emotional reactions of tenants to the acoustic climate at home. An assessment of acoustic comfort in the test apartments was performed utilizing the circumplex model of affect. A sample of 353 residents offered their ratings on 12 bipolar scales regarding their feelings towards their living sound environment. Two dimensions were identified: pleasantness and activation. Statistical models were developed using acoustic and structural variables. $L'_{nT,w,100}$ predicted best pleasantness and number of flats per building predicted best activation. A new acoustic comfort indicator is suggested based on the pleasantness model and four novel acoustic comfort classes are proposed as: AC-1: Very good, AC-2: Good, AC-3: Acceptable, AC-4: No comfort.

Keywords: Acoustic, Comfort, Responses

1. INTRODUCTION

The Cambridge dictionary defines comfort as "a pleasant and satisfying feeling of being physically or mentally free from pain and suffering, or something that provides that feeling" (1). Seemingly, comfort is described as a state of feelings towards a situation. Acoustic comfort is defined in (2) as: "a concept that can be characterized by absence of unwanted sound, desired sounds with the right level and quality, and opportunities for acoustic activities without annoying other people".

Acoustic comfort issues have been treated entirely as noise annoyance problems so far. Usually acoustic data (sound insulation descriptors) were associated to self-reported noise annoyance of the residents (3-6). A detailed review of field surveys following that approach is provided in (7).

Another approach for the evaluation of acoustic environments has been taken with soundscapes. Soundscape is: "an acoustic environment as perceived or experienced and/or understood by a person or people, in context" (8). Background ambience and several random sounds can comprise a soundscape (9). It can be an outside public space: a street or park. The same for indoor climates, such as the living sound environment of an apartment. Assessment of soundscapes can utilize empirical data (interviews) or surveys (questionnaires), as in this study. Subjects can offer ratings on certain scales about a soundscape. Then statistical analysis can reveal the underlying dimensions describing how subjects perceive it. In (10) principal components analysis (PCA) was performed for soundscape perception from ratings on 116 attribute scales of 50 recorded outdoor urban soundscapes. The dimensions of pleasantness, eventfulness and familiarity explained most of the total variance. In (11) visual and acoustic experiments were conducted for the perceived similarity of soundscapes, using 50 recordings from (10). Multidimensional scaling (MDS) revealed three dimensions: distinguishable -indistinguishable sound sources, background-foreground sounds and intrusive-smooth sound sources. In (12) a prediction model was developed for the dimension of vibrancy in soundscapes based on acoustic and visual parameters. There is experimentation with the soundscapes approach in overall, for the evaluation of outdoor spaces, but less applications of soundscapes for indoor spaces.

In this study, we approach acoustic comfort in apartment buildings utilizing soundscapes and

[1] nikolas.vardaxis@construction.lth.se
[2] delphine.bard@construction.lth.se

focusing on human perception and emotions. We explore how the residents feel in their living sound environment. A model of underlying dimensions was employed, namely the circumplex model of affect, a tool developed in psychology to study emotional reactions of subjects (13). The affect circumplex has been applied in assessment of core affects (13,14) and soundscape studies (10-12).

2. METHODS

The study sample includes 31 structures of various types: heavyweight or lightweight. The term heavyweight (HW) refers to typical concrete frame structures and the term lightweight (LW) refers to wooden buildings (cross laminated timber frame). In total there are 94 building units from 31 blocks (1 or more units each) of a certain structure: 24 HW types and 7 LW. Sound transmission measurements took place in the test structures between two typical adjacent rooms, one above another, bedrooms or living rooms. Current standardized methods for airborne sound reduction and impact sound level measurements were followed to characterize insulation of building components according to ISO (15,16). The measurement data were collected from the Green Buildings database, which concerns a Swedish national program about acoustic conditions in dwellings. An overview of the acoustic variables is provided in Table 1. Most structures fulfil the Swedish BBR criteria, which set minimum $D_{nT,w,50}$=52 dB from outside to inside a house and maximum $L'_{nT,w,50}$=56 dB (17).

Table 1 – Single number quantities of acoustic descriptors for the sample structures.

		Airborne sound descriptors		**Impact sound descriptors**	
		$D_{nT,w,50}$	$D_{nT,w,100}$	$L'_{nT,w,50}$	$L'_{nT,w,100}$
Structure type	N	Mean (Range)		Mean (Range)	
Heavy-weight (HW)	24	58.3dB (51-64)	58.7dB (52-65)	49.6dB (40-53)	49.1dB (39-52)
Light-weight (LW)	7	55.5dB (48-63)	56.3dB (48-65)	52.4dB (49-59)	49.5dB (47-54)
All structures	31	57.6dB (48-64)	58.1dB (48-65)	50.2dB (40-59)	49.2dB (39-54)

Furthermore, self-reported data was collected with the development of a questionnaire, for the residents of the test structures, developed according to ISO 15666 (18). The survey aimed to capture several aspects relevant to acoustic comfort. It was distributed using post mail (one copy for every test flat, a web link was provided too): an invitation letter was firstly sent with the questionnaire, then two reminder letters followed within a month. Table 2 presents the question items analyzed in this article.

Table 2 - Question with semantic differentials as presented a survey the about acoustic environment at home. Original version presented in Swedish language as developed in (14).

Different environments can affect the way we feel and our well-being. What effect does your home have on you? Answer each one by circling the number that most accurately describes the way you feel when you come home. Don't spend too much time on each question – we are looking for your immediate reaction. These are scales of opposites, so if you feel more drowsy than alert, circle either number 1 or 2 on the scale. If you are right in between, circle number 3.

a. Sleepy	1	2	3	4	5	Awake
b. Displeased	1	2	3	4	5	Pleased
c. Bored	1	2	3	4	5	Interested
d. Tense	1	2	3	4	5	Serene
e. Passive	1	2	3	4	5	Active
f. Sad	1	2	3	4	5	Glad
g. Indifferent	1	2	3	4	5	Engaged
h. Anxious	1	2	3	4	5	Calm
i. Dull	1	2	3	4	5	Peppy
j. Depressed	1	2	3	4	5	Happy
k. Pessimistic	1	2	3	4	5	Optimistic
l. Nervous	1	2	3	4	5	Relaxed

With a response rate of 27%, 353 observations were collected (158 male, 188 female, 7 unreported). The subjects are 18-85 years old and have spent at least 12 months in their flat. Those who use hearing aids at home were filtered out of the dataset. Tenants living on the top floor were filtered out too, since they do not have neighbors on the floor above and their sound conditions are probably different.

The question items regarding the emotional reactions and perception evaluation of the participants are presented in Table 2. It is simply formulated as: What effect does your home have on you? The questionnaire was entitled "Research project on sound environment in residential buildings". The introduction text as well as most of the questions concerned acoustic issues at home. The results were analyzed in SPSS Statistics 24. PCA was performed for dimension reduction. Linear regression was applied the component loadings in order to develop prediction models for the identified dimensions. Non-parametric Mann-Whitney U-tests were applied to compare independent groups of observations.

Figure 1 depicts the circumplex model of affect as defined in (13,14). It refers to a psychological construct composed of two orthogonal dimensions: pleasantness and activation. They were found sufficient to express the emotional state of subjects and the 12 items of Table 2 were established and validated after experiments for Swedish wording in a study by Västfjäll et al. (14).

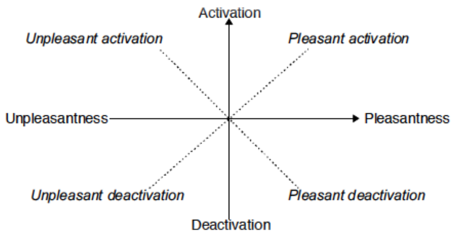


Figure 1 - The affect circumplex model presented in (14).

3. RESULTS AND DISCUSSION

3.1 Individual observations analysis

The mean responses of the residents for the question under study are illustrated in Figure 2. From the total 353 observations, 327 were included in this analysis due to missing values. As can be observed all self-reported rating averages of the participants are on the positive side of the scale (>3), meaning on the side of the reaction scales with the affirmative emotions.

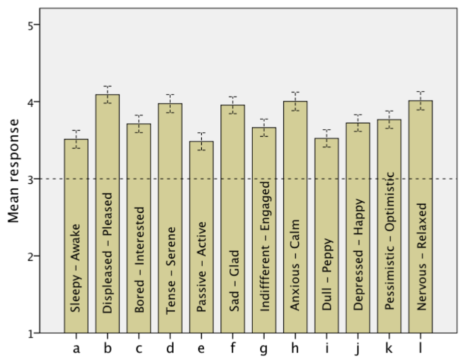


Figure 2 – Mean responses for the sub-items of the question: What effect does your home have on you? Error bars represent 95% C.I.

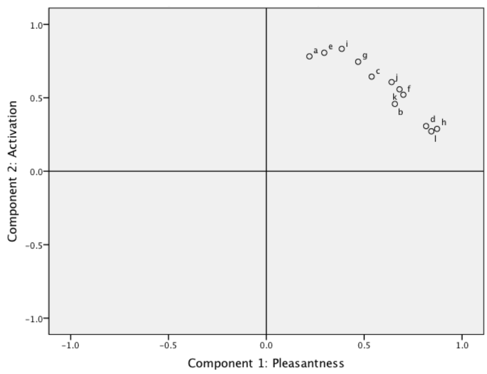


Figure 3 – Component loadings plot for the two dimensions: 1-pleasantness and 2-activation.

Principal components analysis was performed and the Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy offered a sufficient value of 0.948. Varimax rotation was applied to achieve an optimal orthogonal solution. Twelve components were extracted in total but only two of them were selected, after applying a scree criterion based on a minimum eigenvalue of unity. The percentage of the total variance explained was 39.4% and 36.2% for the first and second components respectively. That is a satisfactory solution explaining a cumulative 75.6% of the total variance. The component loadings are presented in Table 3 and their plot on two dimensions is illustrated in Figure 3. The components can be directly interpreted as the two dimensions of pleasantness and activation, as suggested by the valence-activation construct analyzed in (14).

The first component corresponds to the dimension of pleasantness since the adjective pairs: displeased-pleased, sad-glad, depressed-happy load higher on that and they are designed to measure pleasantness emotions (Table 3). The adjective pairs that load higher on the second component are: sleepy-awake, dull-peppy, passive-active, which supposedly measure the dimension of activation.

Table 3 – Component loadings of final the PCA rotated solution.

Semantic differentials	**Component 1 (Pleasantness)**	**Component 2 (Activation)**
a. Sleepy – Awake		0.782
b. Displeased – Pleased	0.657	0.458
c. Bored – interested	0.538	0.644
d. Tense - Serene	0.816	
e. Passive – Active		0.807
f. Sad – Glad	0.700	0.521
g. Indifferent – Engaged	0.469	0.746
h. Anxious – Calm	0.872	
i. Dull – Peppy		0.833
j. Depressed – Happy	0.640	0.607
k. Pessimistic – Optimistic	0.680	0.558
l. Nervous - Relaxed	0.843	
% of variance explained	39.38%	36.16%

Coefficients below 0.40 are suppressed.

All the components load on the positive region for both dimensions (Figures 1 and 3). That is specifically the area of "pleasant activation" as explained in (14). Consequently, the residents perceive their sound environment at home as having a high degree of acoustic comfort in overall. This is expected since most sample buildings comply with the Swedish criteria (17).

Further, we explored possible predictor variables for modeling the identified PCA dimensions. The component loading scores of every observation were used as dependent variables. Other variables from the survey's dataset can be used as independent variables to establish statistical associations with the use of linear regression models. The aim is to develop a prediction model for acoustic comfort using acoustic descriptors and building construction data. The determination coefficients R^2 for linear models predicting the components' loading scores are shown in Table 4. The R^2 represent the total variance explained by the predictor variable. All R^2 values are very low, indicating lack of strong linear relationships probably due to the high variability between all 327 observations. Consequently, no further conclusions could be drawn using the individual responses.

Table 4 - Determination coefficients R^2 for linear predictors of Pleasantness and Activation (individual observations case).

Predictors	**Component 1 Pleasantness**	**Component 2 Activation**
$L'_{nT,w,100}$	0.005	0.033*
$D_{nT,w,100}$	0.001	0.007
$L'_{nT,w,50}$	0.003	0.006
$D_{nT,w,50}$	0.002	0.011
Size (m2)	0.001	0.077*
#Flats	0.014	0.039*
#Tenants	0.012	0.002

* *(Model parameters significant with p<0.05)*

3.2 Clustered observations analysis for heavyweight buildings

The observations are clustered in structure types such as: heavyweight (HW) concrete structures and lightweight (LW) wooden ones. It has been indicated previously that HW and LW structures have quite different acoustic behavior and the perception of residents varies according to structure type

(3,5,21). In this survey, the mean responses for of LW structure groups are higher than HW ones and for 5 items there are statistically significant differences. That was suggested by non-parametric Mann-Whitney U-tests, which indicated significance specifically for items: a ($Z=-3.769$, $p<0.001$), c ($Z=-2.738$, $p<0.01$), e ($Z=-2.132$, $p<0.05$), g ($Z=-2.016$, $p<0.05$) and i ($Z=-2.540$, $p<0.05$).

Additionally, there are not equal sample sizes of observations in the various structure blocks. Thus HW and LW structures are studied separately. Also, the responses are now averaged per structure block: so the replies from a certain structure type are represented by their mean value. For the concrete structures, the same analysis was attempted with better results than in Table 4. However, the R^2 values went as high as 0.2, which is not a sufficient level of correlation. Thus all groups with small sample size were filtered out completely and 9 HW buildings having a sample size n more than 10 observations were analyzed. Finally, 181 observations were included from 9 blocks of heavyweight structures (85 male, 96 female). The initial PCA statistics provided: KMO=0.934, 37.3% and 34.6% of total variance explained by D_1:pleasantness and D_2:activation respectively. Using the 9 blocks ($n>10$) led to better linear associations for the tested variables, as seen in Table 5.

Table 5 – R^2 for linear predictors of Pleasantness and Activation in concrete buildings (HW clustered observations).

Predictors	**Component 1** **Pleasantness**	**Component 2** **Activation**
Size (m2)	0.270	0.136
#Flats	0.117	0.538 *
#Tenants	0.108	0.017
$L'_{nT,w,50}$	0.345	0.248
$L'_{nT,w,100}$	0.478*	0.192
$D_{nT,w,50}$	0.009	0.351
$D_{nT,w,100}$	0.002	0.264
$D_{nT,w,50} + L'_{nT,w,50} + Size + \#Flats$	0.479	0.708
$D_{nT,w,100} + L'_{nT,w,100} + Size + \#Flats$	0.573	0.647

** (Model parameters significant with p<0.05)*

The impact sound index $L'_{nT,w,100}$ is a statistically significant predictor of Pleasantness while the number of flats in a building is a significant predictor of Activation. As for the other acoustic indicators, the airborne sound reduction indices $D_{nT,w,100}$ and $D_{nT,w,50}$ associate well with the dimension of activation only, though with moderate R^2 values. However, number of apartments in a building unit (variable denoted *#Flats*) correlates high enough with activation.

Combinations of the predictor variables were tested in order to develop multiple regression models. The best determination coefficient R^2 is achieved for the relevant variables: both descriptors $L'_{nT,w,100}$, $D_{nT,w,100}$ (or $L'_{nT,w,50}$, $D_{nT,w,50}$) the size of flat and the number of flats in a building. But those models do not have statistical significance for their model parameters (Table 5). The same applies to most variables regardless the R^2 indicated in the models, simple or multiple. Only the univariate models of $L_{nT,w,100}$ and *#Flats* predicting pleasantness and activation respectively have statistically significant parameters ($p<0.05$). A backwards regression process was performed for a model with all variables of Table 5. The results confirmed that the only significant predictors are $L'_{nT,w,100}$ for D_1 and #Flats for D_2. Only those can formulate reliable prediction models of the PCA dimensions as:

$$D_1 = 4.171 - 0.084 \cdot L'_{nT,w,100}$$
$$D_2 = 0.321 - 0.009 \cdot \#Flats$$

Furthermore, using size for a linear model with averaged responses per structure block would not be that reasonable. Size of flats varies within a building and an average size might not be representative of the conditions for all subjects. But the number of flats in a structure is constant (at least in this dataset) and relevant to average responses. Also more flats and residents in a building mean more activity and sounds between apartments, so *#Flats* is sensible to correlate with activation.

Reasonably the impact sound descriptor associates higher with pleasantness, which is related to quietness and noise annoyance. Impact sound descriptors $L'_{nT,w,100}$ or $L'_{nT,w,50}$ have been found to be highly correlated to impact noise types in apartments. The latter have been reported as the most disturbing noise type during numerous subjective annoyance surveys (3-7,19-21).

3.3 Proposal of acoustic comfort index for heavyweight buildings

An acoustic comfort index can be constructed based on the aforementioned models for the prediction of pleasantness and activation. A parametric analysis was performed illustrating the acquired component loadings for various values of $L'_{nT,w,100}$ and #Flats in the models for D_1 and D_2 respectively (Figures 4 and 5). The desirable values for component loadings lie in the region of "pleasant activation" (Fig.1), which corresponds to positive loadings for both dimensions. Loadings bigger than 0 are necessary for positive emotional reactions and good acoustic comfort evaluation. Values bigger than 0.5 would indicate a very good evaluation in the affect circumplex and a high sense of acoustic comfort.

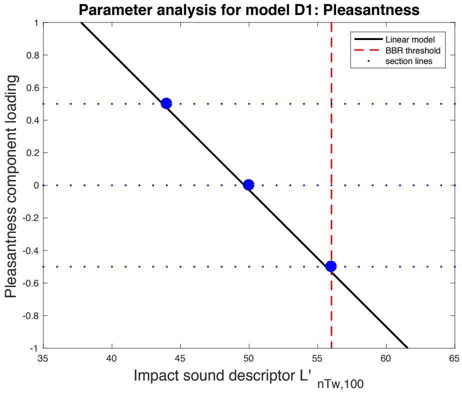


Figure 4 - Parameter analysis in the model of D_1:Pleasantness predicted by $L'_{nT,w,100}$.

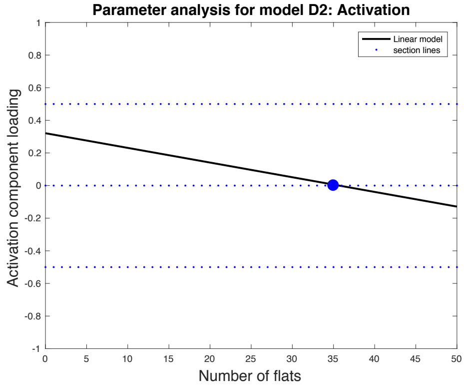


Figure 5 – Parameter analysis in the model of D_2:Activation predicted by $\#Flats$.

For the case of the impact sound index as predictor of D_1:Pleasantness, it is observed that the value of zero corresponds to 50 dB, so above that there is a region of good acoustic comfort with positive ratings in the affect circumplex. Then above a threshold of 0.5 there is a region of very good sense of acoustic comfort, which corresponds to $L'_{nT,w,100}$ values lower than 44 dB. Below a component loading of zero there is a suggested region for an acceptable comfort level between 51-56 dB. The 56 dB value is due to the highest limits set in the Swedish regulations for noise transmission (17), also known as BBR value of Boverket. However, the 56 dB maximum impact noise level is established with the descriptor $L'_{nT,w,50}$, including the low frequency range from 50 Hz. Overall, Table 6 summarizes those regions, according to which an acoustic comfort index with distinct comfort classes is proposed.

For the number of flats predicting the dimension of activation (D_2), the parametric analysis does not offer very clear results (Fig.5). The linear model intersects the zero line at 35, meaning that less than 35 apartments per building unit would be required for good acoustic comfort sense. Then the limit of 0.5 is out of the scope of comparison and no further conclusions can be made about the number of flats and the activation loadings. Further, 35 is not a small number for total flats per building thus it is questionable if that number can really be a parameter for an acoustic comfort index. Considering all that, the acquired linear model for predicting D_2:Activation was neglected. To formulate a new acoustic comfort descriptor, only the model of $L'_{nT,w,100}$ predicting pleasantness was utilized. The equation for the new proposed acoustic comfort indicator is then:

$$AC_{index} = 4.171 - 0.084 \cdot L'_{nT,w,100}.$$

Noticeably the new acoustic comfort index should take values between -1 and 1, an assumption compliant with the maximum or minimum component loadings. The linear model can return values outside the reasonable limits [-1,1] but such values are neglected. Positive values are needed for a good evaluation. The condition $AC_{index}>0$ can help identify the suggested acoustic comfort classes: AC-1 or AC-2, as tabulated in Table 6. The threshold value of 0.5 for an average component loading separates AC-1 and AC-2 characterized as "Very Good and "Good" respectively.

The negative values correspond to the lower comfort classes AC-3 and AC-4, that being the categories characterized as "Acceptable" and "Not acceptable" respectively (Table 6). The AC-3 region (AC_{index} values between -0.5 and 0) relates to low comfort evaluation but still acceptable according to the Swedish regulation limits (17). The index values below -0.5 denote the worst region for acoustic comfort perception, that is the class AC-4.

Table 6 presents also a comparison with the acoustic classes established by the Swedish acoustic standard (21) which uses $L'_{nT,w,50}$ instead for impact sound level descriptor. Class D has the same maximum limit as the suggested AC-4: impact sound level index more than 56 dB correspond to the worst class. Then Class C is defined for $L'_{nT,w,50}$ values between 56-53 dB, Class B for values 52-48 dB and Class A for $L'_{nT,w,50}$ values lower than 48 dB. The values of the suggested classes AC-3, AC-2 and AC-1 are a bit lower, meaning that the acoustic comfort classes derived in this study have stricter criteria than the standardized classes.

Table 6 - Acoustic comfort index and classes suggestion for heavyweight structures. Comparison with Swedish classification of SIS SS 25267 standard (21).

Comfort category	**No comfort**	**Acceptable**	**Good**	**Very good**
Index class	**AC-4**	**AC-3**	**AC-2**	**AC-1**
AC_{index}	< -0.5	-0.5 - 0	0.01-0.5	> 0.5
$L'_{nT,w,100}$	> 56 dB*	56-51 dB	50-45 dB	< 44 dB
Swedish standard (23)	Class D	Class C	Class B	Class A
$L'_{nT,w,50}$	> 56 dB*	56-53 dB	52-48 dB	< 48 dB

** BBR minimum value (17)*

3.4 Clustered observations analysis for lightweight structures

The same analysis was performed for the case of LW structures in order to find variables that predict the PCA dimensions and formulate a similar acoustic comfort model as before. Namely, 77 observations from 6 blocks of LW structures were included. A minimum sample size of n=5 per LW block was applied, due to less groups and observations. Initial PCA provided: KMO=0.923, 45.2% and 34.8% of total variance explained by D_1:pleasantness and D_2:activation respectively. However, no linear model had statistical significance in model parameters to be reliable enough. Hence, a concluding acoustic comfort model for LW structures could not be proposed.

4. CONCLUSIONS

The acoustic comfort was investigated in a sample of Swedish apartment buildings. A comfort assessment was performed, based on the emotional reactions of the residents towards their sound environment at home. The circumplex model of affect (14) was deployed for evaluation. The results indicated a very positive perception in overall according to the semantic differential scales used in model, indicating affirmative emotional states of the residents in their apartments.

Principal component analysis was performed and two dimensions were identified: pleasantness and activation, which explain 39.4% and 36.2% of the variance respectively, namely 75.6% of the total variance. This is a confirmation of the dimensions suggested by the affect circumplex model (13) and especially for the Swedish version with 12 sub-items used in this study case (14).

The development of statistical models was attempted based on the prediction of component loading scores by variables relevant to the structure and the acoustic conditions. The acoustic descriptors $L'_{nT,w,100}$ and $D_{nT,w,100}$, the size of apartments, the number of occupants in a flat and the number of total flats in a building were tested.

Linear models could not be developed for the case of individual observations due to high variability in the dataset. However, when the observations were treated as grouped in structures and their responses were averaged per structure block, sufficient correlations could be established. For the case of heavyweight (HW) concrete buildings, prediction models were developed for the two identified dimensions. $L'_{nT,w,100}$ was the best predictor for D_1:pleasantness and number of flats predicted best the dimension D_2:activation. Multiple regression models were tested as well, but they failed in terms of statistical significance for their estimated model parameters.

Furthermore, a novel acoustic comfort index for concrete buildings is suggested, based on the statistical model for the prediction of pleasantness. The suggested descriptor is formulated as: AC_{index}= 4.171-0.084·$L'_{nT,w,100}$. Based on the new index and its scale, 4 classes of acoustic comfort are suggested as AC-1: Very good, AC-2: Good, AC-3: Acceptable, AC-4: No acoustic comfort.

For the lightweight (LW) wooden building structures of this survey, the statistical results were not sufficient for prediction models. The total observations and the sample size of LW blocks were much lower than for the HW data groups. Further individual research should be applied in lightweight structures to establish a separate model for acoustic comfort.

REFERENCES

1. Cambridge Dictionary, website: https://dictionary.cambridge.org/dictionary/english/comfort, last search on May 5th, (2019).
2. Rasmussen B., Rindel J.H., Sound insulation between dwellings - Requirements in building regulations in Europe, J. Applied Acoustics 71, 2010, 373-385.
3. Ljunggren F., Simmons C., Hagberg K., "Correlation between sound insulation and occupants' perception – Proposal of alternative single number rating of impact sound", Applied Acoustics 85, 2014, 57-68.
4. Hagberg K., Bard D., "Low frequency sound transmission in multifamily wooden houses" Inter-noise 2014, Melbourne, Australia, 2014.
5. Ljunggren F., Simmons C., Öqvist R., "Correlation between sound insulation and occupants' perception – Proposal of alternative single number rating of impact sound-Part II", Applied Acoustics 123, 2017.
6. Milford I., Høsøien C.O., Løvstad A., Rindel J. H., Klæboe R., "Socio-acoustic survey of sound quality in Dwellings in Norway", Proceedings Inter-noise 2016, Hamburg, Germany, 2016.
7. Vardaxis N.G., Bard D., Persson Waye K., Review of acoustic comfort evaluation in dwellings – Part I: Associations of acoustic field data to subjective responses from building surveys, Building Acoustics, 25(2), 2018, 151–170.
8. ISO 12913-1:2014 "Acoustics – Soundscape – Part 1: Definition and conceptual framework." (International Organization for Standardization, Geneva, Switzerland), 2014.
9. Truax B., Handbook for Acoustic Ecology, No. 5, Music of the Environment Series, World Soundscape Project, A.R.C. Publications, 1978.
10. Axelsson Ö., Nilsson M.E., Berglund B., A principal components model of soundscape perception, J. Acoust. Soc. Am. 128(5), 2010.
11. Aletta F., Axelsson Ö., Kang J., Dimensions underlying the perceived similarity of acoustic environments, Front. Psychol 8:1162, 2017.
12. Aletta F., Kang J., Towards an Urban Vibrancy Model: A Soundscape Approach, Int. J. Environ. Res. Public Health 2018(15:1712), 2018.
13. Russel J. A., A circumplex model of affect, J. Personality and Social Psychology 39(6):1161-1178,1980.
14. Västfjäll D., Friman M., Gärling T., Kleiner M., The measurement of core affects: A Swedish self-report measure derived from the affective circumplex. Göteborg Psychological Reports, 2000(30), No.8, 2000.
15. ISO 16283 "Field measurement of sound insulation in buildings and of building elements, - Part 1: Airborne sound insulation, - Part 2: Impact sound insulation" (International Organization for Standardization, Geneva, Switzerland), 2014.
16. ISO 12354 "Building Acoustics – estimation of acoustic performance of buildings from the performance of elements, – Part 1: Airborne sound insulation between rooms, – Part 2: Impact sound insulation between rooms" (International Organization for Standardization, Geneva, Switzerland), 2017.
17. Boverket, Boverket´s building regulations – mandatory provisions and general recommendations, BBR, Sweden, Boverket The Swedish National Board of Housing, Building and Planning, 2016.
18. ISO 15666 "Acoustics - Assessment of noise annoyance by means of social and socio-acoustic surveys" (International Organization for Standardization, Geneva, Switzerland), 2003.
19. R. Öqvist, F. Ljunggren, R. Johnsson, Listening test of walking noise from 20 Hz in dwellings, Proceedings Inter-noise 2017, 3935-3942, Hong Kong, China, 2017.
20. Park S. H., Lee P. J., Reaction to floor impact noise in multi-storey residential buildings: The effects of acoustic and non-acoustic factors. Applied Acoustics 2019 (150): 268–278.
21. SIS SS 25267, Acoustics- Sound classification of spaces in buildings – Dwellings (in Swedish), Swedish Standards Institute, Stockholm, Sweden, 2015.

Appendix A

LUND UNIVERSITY

Research project:

Sound environment in residential buildings

Hi!

We would like to invite you who live in this residential area to be part of our research project on sound environments in residential houses.

To participate and respond to the survey electronically, please visit XXXXX. If you would prefer the survey on paper, please contact us by emailing XXXXX. Your responses and results will be treated confidentially, in accordance with the Swedish Data Protection Act. Please read the information provided on the back of this letter.

If you have any questions, please contact us via email, regular mail or telephone.

Kind regards

Delphine Bard

Associate professor, project manager

Lund University, LTH

072 526 2202

Email: delphine.bard@construction.lth.se

Kerstin Persson Waye

Professor,

University of Gothenburg

031 786 3604

Email: kerstin.persson-waye@amm.gu.se

Nikolas Vardaxis

Doctoral student,

Lund University, LTH

072 282 7539

Email: nikolas.vardaxis@construction.lth.se

Firstly, we would like to ask you a few questions about your home.

1. How long have you lived in your home?	a. .... (years)
2. What type of building do you live in?	1 ☐Apartment building 2 ☐Terraced house 3 ☐Detached house
3. On what floor do you live?	1 ☐Ground floor 2 ☐Top floor 3 ☐Other ....
4. What is the size of your home?	.... m^2
5. Does your bedroom window face a: (Select all that apply)	1 ☐ Local street 2 ☐Main road 3 ☐Motorway 4 ☐Train/tram tracks 5 ☐Yard/park 6 ☐Shops/other activity
6. How many people, including you, are currently living <u>in your home</u>?	......
7. Do you have children living with you on a regular basis?	a. 1 ☐No 2 ☐Yes b. Age/s ....

The following questions concern the sound environment in your home.

8. Thinking about the last 12 months, when you are here at home, how would you describe the sound quality in your home when all windows and doors are shut? *Answer each one by circling the number that most accurately describes your situation.* Don't spend too much time on each question – we are looking for **your immediate reaction.**

	Not at all	Slightly	Moderately	Very	Extremely
a. Quiet	1	2	3	4	5
b. Soft	1	2	3	4	5
c. Muffled	1	2	3	4	5
d. Loud	1	2	3	4	5
e. Hard	1	2	3	4	5
f. Pleasant	1	2	3	4	5
g. Sharp	1	2	3	4	5
h. Comfortable	1	2	3	4	5
i. Noisy	1	2	3	4	5
j. Rattling	1	2	3	4	5
k. Buzzing	1	2	3	4	5
l. Unpleasant	1	2	3	4	5
m. Echoing	1	2	3	4	5
n. Calm	1	2	3	4	5
o. Grinding	1	2	3	4	5
p. Not soundproof	1	2	3	4	5

Further comments:

....

....

9. Thinking about the last 12 months, when you are here at home…

	Not at all	Slightly	Moderately	Very	Extremely
a. *How much do you think about* not disturbing your neighbours when you e.g. play music, close doors, or walk around?	1	2	3	4	5
b. *How disturbed/bothered* do you think your neighbours are from the noise you make?	1	2	3	4	5

The following questions concern specific sources of sound that you may hear when you are at home.

10. Thinking about the last 12 months, when you are here at home, *with the windows and doors shut, how much* disturbed are you by:

	Not at all	Slightly	Moderately	Very	Extremely
a. **Noise from machines or appliances inside the building**? (Refrigerator, freezer, washer, dryer, lift, AC, ventilation, water pipes, flushing toilets)	1	2	3	4	5
b. **Low-frequency noise** from a neighbour's sound system, TV or computer, coming through the walls?	1	2	3	4	5
c. **Low-frequency noise** from a neighbour's sound system, TV or computer, coming through the floor or ceiling?	1	2	3	4	5
d. **Sound of neighbours talking,** coming through the walls?	1	2	3	4	5
e. **Sound of neighbours talking,** coming through the floor or ceiling?	1	2	3	4	5
f. **Sound of neighbours walking**, slamming doors and dropping things, thuds from children playing, coming through the floor or ceiling?	1	2	3	4	5
g. **Sound of walking** in shared spaces of the building (staircase, hallway, etc.)?	1	2	3	4	5
h. **Low-frequency noise** (rumbling, muffled sound) from **outside sources such as music, traffic and ventilation**?	1	2	3	4	5

The following questions concern your sleep

11. How would you rate your normal quality of sleep?

1 ☐Very good	2 ☐Fairly good	3 ☐Neither good nor bad	4 ☐Fairly bad	5 ☐Very bad

12. In a regular week, how often does noise disturb your sleep?

1 ☐Not at all	2 ☐1–2 times/ week	3 ☐3–4 times/week	4 ☐5–6 times/week	5 ☐Every night

If you ticked the box "3–4 times/week" or more, describe the noise that is disturbing you?

....

....

13. Thinking about the last 12 months, when you are here at home with the windows and doors shut, how *much is your sleep disturbed by:*

	Not at all	**Slightly**	**Moderately**	**Very**	**Extremely**
a. **Noise from machines or appliances inside the building**? (Refrigerator, freezer, washer, dryer, lift, AC, ventilation, water pipes, flushing toilets)	1	2	3	4	5
b. **Low-frequency noise** from a neighbour's sound system, TV or computer?	1	2	3	4	5
c. **Sound of neighbours talking**?	1	2	3	4	5
d. **Sound of neighbours walking**, slamming doors and dropping things, thuds from children playing?	1	2	3	4	5
e. **Sound of walking** in **shared** spaces of the building (staircase, hallway, etc.)?	1	2	3	4	5
f. **Low-frequency noise** (rumbling, muffled sound) from outside sources such as music, traffic and ventilation?	1	2	3	4	5

14. Are you considering moving from your home due to noise pollution? 1 ☐No 2 ☐Yes

15. Is there any other disturbing source of noise in or close to your home that we have not addressed?

a. 1 ☐No 2 ☐Yes b. If so, please indicate the level of disturbance:

1 ☐Not at all	2 ☐Somewhat	3 ☐Fairly	4 ☐Very	5 ☐Extremely

If you ticked the box for "Fairly" or higher, please describe the source:

....

....

16. Different environments can affect the way we feel and our well-being. What effect does your home have on you? *Answer <u>each one</u> by circling the number that most accurately describes the way you feel when you come home*. Don't spend too much time on each question – we are looking for **your immediate reaction.** These are scales of opposites, so if you feel *more* drowsy than alert, circle either number 1 or 2 on the scale. If you are right in between, circle number 3.

a. Sleepy	1	2	3	4	5	Awake
b. Displeased	1	2	3	4	5	Pleased
c. Bored	1	2	3	4	5	Interested
d. Tense	1	2	3	4	5	Serene
e. Passive	1	2	3	4	5	Active
f. Sad	1	2	3	4	5	Glad
g. Indifferent	1	2	3	4	5	Engaged
h. Anxious	1	2	3	4	5	Calm
i. Dull	1	2	3	4	5	Peppy
j. Depressed	1	2	3	4	5	Happy
k. Pessimistic	1	2	3	4	5	Optimistic
l. Nervous	1	2	3	4	5	Relaxed

17. How pleased are you with the sound environment in your home?

1 ☐Very pleased	2 ☐Fairly pleased	3 ☐Neither pleased nor displeased	4 ☐Fairly displeased	5 ☐Very displeased

Finally, a few questions about you:

18. Gender: 1 ☐Man 2 ☐ Woman

19. What year were you born? ……………………… (YYYY)

20. How would you describe your sensitivity to sound?

1 ☐Not at all sensitive	2 ☐Somewhat sensitive	3 ☐Fairly sensitive	4 ☐Very sensitive	5 ☐Extremely sensitive

21. Do you regularly use hearing aids at home? 1 ☐No 2 ☐Yes

22. In the *last 12 months*, how would you describe your health?

1 ☐Very good	2 ☐Good	3 ☐Neither good nor bad	4 ☐ Bad	5 ☐Very bad

The following questions are to determine whether the participants in the survey are representative of society at large.

23. Are you:

1 ☐Single	2 ☐In a cohabiting/ live apart relationship	3 ☐Married	4 ☐Divorced	5 ☐Widow/er	6 ☐Other

24. Were you born in Sweden? 1 ☐No 2 ☐Yes

25. If No, how long have you lived in Sweden? …… years

26. What is your highest completed level of education? (Chose one option)

1 ☐Elementary/primary school	2 ☐Upper secondary school/high school	3 ☐University

27. What is your current occupation?

1 ☐Student	5 ☐Unemployed
2 ☐Stay at home parent /parental leave	6 ☐Employed (currently working)
3 ☐On sick leave	7 ☐Other
4 ☐On a leave of absence	

28. What is your household's total monthly income before tax?

1 ☐SEK 0–14 999/month	2 ☐SEK 15000–29 999/month	3 ☐SEK 30 000–44 999/month	4 ☐SEK 45 000–59 999/month	5 ☐SEK 60 000 or more/month

29. Would you recommend your place of residence to someone else? 1 ☐No 2 ☐Yes

Further comments (optional):

………

………

………

30. May we contact you to conduct possible sound level measurements?

1 ☐No, I do not wish to be contacted
2 ☐Yes, contact me via phone/email ....

Thank you for your help!

Forskningsprojekt om

Ljudmiljö i bostäder

Hej!

Vi vill bjuda in dig som bor i detta bostadsområde att delta i vårt forskningsprojekt om ljudmiljö i bostäder.

För att delta och besvara formuläret elektroniskt, var snäll och klicka på webbadressen http://bit.ly/2sGM3wX eller skanna QR-koden. Om ni hellre önskar ett pappersformulär hör av er till oss på mailadress: nikolas.vardaxis@construction.lth.se. Dina svar och dina resultat kommer att behandlas så att inte obehöriga kan ta del av dem och behandlas i enlighet med personuppgiftslagen. Vänligen läs igenom informationen på baksidan av detta brev.

OBS! Undersökningen gäller endast för personer i ålder 18-85. Om det finns fler än en vuxen i hushållet ska personen med födelsedatum närmast den 1 december delta.

Om du har några frågor är du välkommen att kontakta oss via e-post, brev eller telefon!

Vänliga hälsningar

Delphine Bard
Ass. Professor, projektansvarig
Lund Universitet, LTH
072-526 2202
Email: delphine.bard
@construction.lth.se

Kerstin Persson Waye
Professor,
Göteborgs Universitet
031 - 786 3604
Email: kerstin.persson.waye
@amm.gu.se

Nikolas Vardaxis
Doktorand,
Lund Universitet, LTH
072-282 7539
Email: nikolas.vardaxis
@construction.lth.se

Bakgrund och syfte

Vi vet sedan tidigare projekt att krav på ljudisolering och andra parametrar kan vara missvisande med hänsyn till hur människor upplever störning. Tidigare forskning har indikerat att vissa byggnadskonstruktioner kräver nya sätt att mäta och värdera ljudisolering mellan olika utrymmen så att det stämmer bättre med hur det upplevs. Detta forskningsprojekt avser att fördjupa kunskapen om dessa samband genom att kombinera svar på utprovade frågeformulär med mätningar från olika byggnadskonstruktioner, och även olika materialval, för att kunna ytterligare bättre förstå vilka mekanismer som styr akustisk komfort i byggnader. Forskningsprojektet finansieras av Weber – Saint Gobain.

Förfrågan om deltagande

Du inbjuds till att medverka i detta projekt eftersom du bor i en byggnad som är av stort intresse för detta projekt. Vi har efter etisk prövning fått tillgång till din adress och ditt namn via skatteverkets befolkningsregister.

Hur går denna studie till?

Vi har till Er skickat ett brev med en webbadress med länk till ett formulär som vi ber dig fylla i. Om ni istället önskar ett vanligt formulär som ni besvarar med penna, var snäll och hör av er till nikolas.vardaxis@construction.lth.se , så skickar vi det per post. För att delta klickar du på länken till webbadressen http://bit.ly/2sGM3wX där du kan besvara frågeformuläret elektroniskt. Med hjälp av dina svar får vi kunskap om ljudmiljön i den byggnad du bor i, hur du upplever olika typer av ljud inom bostaden samt andra närliggande aspekter. Du kan bli kontaktad för kompletterande frågor i den händelse att svaren är svårtolkade och du får då ytterligare information. Du kan naturligtvis avstå att medverka i den kompletterande undersökningen även om du blir kontaktad. Om du ger din tillåtelse kan du bli kontaktad för uppföljande akustiska mätningar i din bostad, du får då ytterligare information.

Vilka är riskerna?

Att delta i denna studie medför inga hälsorisker.

Finns det några fördelar?

Ljudmiljön och dess konsekvenser för boende och hälsa är fortfarande bristfälligt undersökt och de krav som ligger till grund för nuvarande regelverk baseras mycket på schablonberäkningar. Detta projekt kan därför bidra till ny kunskap, som kan ge underlag till modernare krav och klokare materialval. –Projektet bidrar till att framtida byggbestånd kan optimeras betydligt bättre, då rätt material placeras ”på rätt plats” för bästa möjliga ljudmiljö.

Hantering av data och sekretess

Data som samlas in är dina svar på frågeformuläret och adress. Dina svar och dina resultat kommer att behandlas så att inte obehöriga kan ta del av dem. All data sparas kodat och avidentifierat på datamedium som förvaras i låsta utrymmen där endast behöriga forskare har åtkomst. Endast behöriga forskare har tillgång till den kodnyckel som kan identifiera dina svar. Denna kodnyckel förvaras i låst utrymme separat från data. Insamlat material sparas i 10 år för att möjliggöra granskning samt i enlighet med universitetets rutiner för att möjliggöra uppföljande studier. Du har rätt att begära registerutdrag samt att rätta eventuella felaktiga uppgifter. Redovisning av resultaten från projektet kommer att ske i vetenskapliga tidskrifter, vid konferenser samt via Göteborgs Universitet och Arbets- och Miljömedicins (hemsida www.amm.se) och Lunds Universitets, Teknisk Akustik, (hemsida www.acoustics.lth.se). All redovisning sker på gruppnivå där dina svar är anonyma. Ansvarig för dina personuppgifter är Lunds Universitet. Alla personuppgifter hanteras enligt personuppgiftslagen (1998:204).

Hur får jag information om studiens resultat?

Information om resultat av enkätstudien kan fås av projektansvarig och på samma sätt kan deltagare begära att få ta del av sina individuella data.

Försäkring, ersättning

Patientskadeförsäkring samt särskilt tecknad personskadeförsäkring gäller vid eventuellt deltagande i den fördjupade undersökningen. Ingen ersättning ges för deltagande i projektet.

Frivillighet

Att delta i projektet är frivilligt. Du kan välja att besvara frågeformuläret och ändå sedan avstå från att delta i eventuell kompletterande undersökning. Du kan också när som helst avbryta din medverkan, utan att behöva ange någon förklaring. Du kan då själv begära att få redan insamlad data raderad. Om du i efterhand vill avbryta ditt deltagande – vänligen kontakta projektansvarig.

Ansvariga

Forskningshuvudman är Lunds Universitet. Huvudansvarig för projektet är Associate professor Delphine Bard vid Lunds Universitet, teknisk akustik och professor Kerstin Persson Waye vid Arbets- och miljömedicin, avdelningen för Samhällsmedicin och folkhälsa vid Göteborgs universitet.

Inledningsvis skulle vi vilja ställa några frågor om din bostad.

1. Hur länge har du bott i din bostad?	a. …….. (År)
2. Vilken typ av hus bor du i?	1 ☐Flerbostadshus 2 ☐Radhus 3 ☐Villa/ enfamiljshus
3. På vilket våningsplan bor du?	1 ☐Bottenvåningen 2 ☐Högst upp 3 ☐Annat våningsplan ....
4. Hur stor är din bostad?	……… m^2
5. Har ditt sovrum fönster som vetter mot: (Du kan välja flera alternativ)	1 ☐ Lokalgata 2 ☐Landsväg 3 ☐Motorväg 4 ☐ Järnväg/spårvagn 5 ☐ Gård/parkområde 6 ☐ Affärer/annan verksamhet
6. Hur många människor bor det totalt i din bostad inklusive dig själv?	......
7. Har du barn som bor regelbundet hos dig?	a. 1 ☐Nej 2 ☐Ja b. vilka åldrar: ………..

Följande frågor rör ljudmiljön i din bostad.

8. När du tänker på *de senaste 12 månaderna när du är hemma,* hur skulle du vilja beskriva ljudkvalitén i din bostad med fönster och dörrar stängda. *Besvara varje rad med att ringa in den siffra som stämmer bäst.* Gå igenom frågorna utan att tänka för länge, vi vill att du anger **din omedelbara reaktion.**

Stämmer	**Inte alls**	**Något**	**Ganska mycket**	**Mycket**	**Oerhört**
a. Tyst	1	2	3	4	5
b. Mjuk	1	2	3	4	5
c. Dämpad	1	2	3	4	5
d. Högljudd	1	2	3	4	5
e. Hård	1	2	3	4	5
f. Behaglig	1	2	3	4	5
g. Skarp	1	2	3	4	5
h. Bekväm	1	2	3	4	5
i. Bullrig	1	2	3	4	5
j. Skramlande	1	2	3	4	5
k. Surrande	1	2	3	4	5
l. Obehaglig	1	2	3	4	5
m. Ekande	1	2	3	4	5
n. Lugn	1	2	3	4	5
o. Malande	1	2	3	4	5
p. Lyhörd	1	2	3	4	5

Egna kommentarer;

....

....

9. När du tänker på de senaste 12 månaderna, när du är hemma i din bostad?

	Inte alls	**Något**	**Ganska mycket**	**Mycket**	**Oerhört**
a. *Hur mycket tänker* du på att inte störa dina grannar, när du t. ex. spelar musik, stänger dörrar, eller går över golv?	1	2	3	4	5
b. *Hur störda/besvärade* tror du att dina grannar är av buller som du orsakar?	1	2	3	4	5

10. Följande frågor rör specifika ljudkällor som kan höras i bostaden. När du tänker på *de senaste 12 månaderna*, när *du är hemma i din bostad med fönster och dörrar stängda* hur störd är du av:

	Inte alls	**Något**	**Ganska mycket**	**Mycket**	**Oerhört**
a. **Buller från maskiner eller tekniska installationer i byggnaden** (kyl/frys, tvättmaskiner, torktumlare, hiss, luftkonditionering, ventilation, vattenledningar, spolande toaletter)	1	2	3	4	5
b. **Lågfrekvent buller** (basljud) från grannars musikanläggning, TV eller datorer som hörs genom väggen?	1	2	3	4	5
c. **Lågfrekvent buller** (basljud) från grannars musikanläggning, TV eller datorer som hörs genom golvet eller taket?	1	2	3	4	5
d. **Grannars prat** som hörs genom väggen?	1	2	3	4	5
e. **Grannars prat** som hörs genom golvet eller taket?	1	2	3	4	5
f. **Ljud från grannars steg**, smällande i dörrar, saker som tappas i golvet, dunsar från lekande barn som hörs genom golvet eller taket?	1	2	3	4	5
g. **Ljud från steg** från gemensamma utrymmen (trappuppgång, korridor etc) i huset?	1	2	3	4	5
h. **Lågfrekvent buller** (mullrande, dovt ljud) från ljudkällor **utomhus som musik, trafik och ventilation?**	1	2	3	4	5

Följande frågor rör din sömn

11. Hur vill du bedöma din normala sömnkvalitet?

1 ☐Mycket bra	2 ☐Ganska bra	3 ☐Varken bra eller dåligt	4 ☐Ganska dåligt	5 ☐Mycket dåligt

12. Hur ofta störs din sömn av buller under en vanlig vecka?

1 ☐Inte alls	2 ☐ 1-2 ggr/ vecka	3 ☐3-4 ggr/vecka	4 ☐5-6 ggr/vecka	5 ☐Varje natt

Om du kryssat för 3-4 gånger per vecka eller mer, vad är det för buller som du störs av?

....

....

13. När du tänker på de senaste 12 månaderna, när du är hemma (med fönster och dörrar stängda) hur ***mycket störs din sömn av:***

	Inte alls	**Något**	**Ganska mycket**	**Mycket**	**Oerhört**
a. **Buller från maskiner eller tekniska installationer i byggnaden** (kyl/frys, tvättmaskiner, torktumlare, hiss, luftkonditionering, ventilation, vattenledningar, spolande toaletter)	1	2	3	4	5
b. **Lågfrekvent buller** (basljud) från grannars musikanläggning, TV eller datorer?	1	2	3	4	5
c. **Grannars prat**?	1	2	3	4	5
d. **Ljud från grannars steg**, smällande i dörrar, saker som tappas i golvet, dunsar från lekande barn?	1	2	3	4	5
e. **Ljud från steg** från **gemensamma** utrymmen (trappuppgång, korridor etc) i huset?	1	2	3	4	5
f. **Lågfrekvent buller** (mullrande, dovt ljud) från ljudkällor utomhus som musik, trafik och ventilation?	1	2	3	4	5

14. Funderar du på att flytta från din lägenhet på grund av bullerstörning? 1 ☐Nej 2 ☐Ja

15. Är du störd av någon annan bullerkälla i eller i närheten av ditt hem som vi missat att ta upp tidigare?

a. 1 ☐Nej 2 ☐Ja b. i så fall ange grad av störning, Störs du:

1 ☐Inte alls	2 ☐Något	3 ☐Ganska mycket	4 ☐Mycket	5 ☐Oerhört

Ifall du angivit *ganska mycket* eller *högre störning,* beskriv gärna källan:

....

....

16. Vilken inverkan tycker du att din bostad har på dig? Olika miljöer kan påverka hur vi känner oss och vårt välbefinnande. ***Besvara genom att för varje rad ringa in den siffra på skalan som bäst beskriver hur du vanligen känner dig när du kommer hem till din bostad?*** Gå igenom frågorna utan att tänka för länge, vi vill att du anger **din omedelbara reaktion.** Skalorna beskriver motsatser, så om du känner dig *mer* slö än pigg anger du 1 eller 2 på skalan. Om du känner dig mittemellan slö och pigg anger du 3 på skalan.

a. Sömnig	1	2	3	4	5	Vaken
b. Missnöjd	1	2	3	4	5	Belåten
c. Uttråkad	1	2	3	4	5	Intresserad
d. Spänd	1	2	3	4	5	Avspänd
e. Passiv	1	2	3	4	5	Aktiv
f. Ledsen	1	2	3	4	5	Glad
g. Oengagerad	1	2	3	4	5	Engagerad
h. Orolig	1	2	3	4	5	Lugn
i. Slö	1	2	3	4	5	Pigg
j. Nedslagen	1	2	3	4	5	Munter
k. Pessimistisk	1	2	3	4	5	Optimistisk
l. Nervös	1	2	3	4	5	Avslappnad

17. Hur nöjd är du med ljudmiljön i din bostad?

1 ☐Mycket nöjd	2 ☐Ganska nöjd	3 ☐Varken nöjd eller missnöjd	4 ☐Ganska missnöjd	5 ☐Mycket missnöjd

Slutligen några frågor om dig själv:

18. Är du? 1 ☐Man 2 ☐ Kvinna

19. Vilket år är du född? **……………………** (ange 4 siffror)

20. Hur skulle du beskriva din känslighet för ljud?

1 ☐Inte alls känslig	2 ☐Något känslig	3 ☐Ganska känslig	4 ☐Mycket känslig	5 ☐Oerhört känslig

21. Använder du regelbundet hörselhjälpmedel när du är hemma? 1 ☐Nej 2 ☐Ja

22. Hur skulle du vilja bedöma din hälsa under de senaste 12 månaderna?

1 ☐Mycket bra	2 ☐Bra	3 ☐Varken bra eller dålig	4 ☐ Dålig	5 ☐Mycket dålig

Följande frågor ställs för att vi skall kunna ha en uppfattning om hur väl de som deltager i denna undersökning motsvarar samhället i stort.

23. Är du:

1 ☐Ensamstående	2 ☐Sambo / Särbo	3 ☐Gift	4 ☐Skild	5 ☐Änka / Änkling	6 ☐Annat

24. Är du född i Sverige? 1 ☐Nej 2 ☐Ja

25. Om nej, hur länge har du bott i Sverige? …… År

26. Vad är din högsta avslutade utbildningsnivå? (ange ett alternativ)

1 ☐Grundskola / folkskola /realskola eller liknande	2 ☐Gymnasium	3 ☐Universitet

27. Vad är din nuvarande sysselsättning?

1 ☐Studier	5 ☐Arbetslös
2 ☐Hemarbetande / föräldrarledig	6 ☐Yrkesarbetande
3 ☐Sjukskriven	7 ☐Övrigt
4 ☐Tjänstledig	

28. Hur stor är hushållets ungefärliga sammanlagda månadsinkomst före skatt?

1 ☐0-14 999 kr/mån	2 ☐15000-29999/ mån	3 ☐30 000-44 999/ mån	4 ☐45 000-59 999/mån	5 ☐60 000 eller mer/mån

29. Skulle du rekommendera din lägenhet till någon annan? 1 ☐Nej 2 ☐Ja

Nedan kan du ge ytterligare kommentarer:

………

……

………………………………………………………………………………………………………

30. Får vi kontakta dig för eventuella ljudnivåmätningar?

1 ☐Nej, jag vill inte bli kontaktad
2 ☐Ja, kontakta mig på telefonnummer/mailadress ....

Tack för din hjälp!