Subjective Estimation of Airborne Sound Insulation

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Abstract

This study explores airborne sound insulation as an objective and subjective measure.

The concept of this study starts with a hypothesis that there is a need to assess airborne sound insulation in terms of a hearing related measure. Firstly, this study examines how the airborne sound insulation is determined in current standards and how it is affected using different sound signals. To quantify the sound insulation effect of different sound signals and to allow investigating the results numerically, a series of measurements have been carried out. To assess the differences in the evaluation of source signals, electronic filters were generated as well as subjective tests were conducted. The overall results for each research topic can be summarised as follows: Airborne sound insulation determined according to current standards, does not reflect the subjectively perceived sound insulation. It was proven that sound pressure level difference as well as loudness level difference does not relate well to subjectively assessed sound insulation. The introduced loudness level based model correctly depicts the experimental results of the loudest and quietest sound samples as well as the individual frequency dips in the airborne sound insulation. Results of field measurements show that subjectively assessed airborne sound insulation differ from objectively judged airborne sound insulation using descriptors of current standards. Measurements made with different sound signals indicate that the subjectively judged sound insulation is depending on the type of source signal. The model correctly identifies different sound signals relating a measure of "reliable" and "not reliable" in terms of a subjective assessed measure with respect to the predicted value. Thus, the model describes the probability that a measured or computed airborne sound insulation corresponds to the subjectively assessed airborne sound insulation.

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CONTENTS

GLOSSARY OF SYMBOLS AND ABBREVIATIONS

A	Equivalent sound absorption area, (m²)
ANSI	American national standards institute
B	Bulk modulus, (Pa)
C	Spectrum adaptation term, (dB)
CEN	European Committee for Standardization
c	Speed of sound, (ms^{-1})
c_L	Longitudinal speed of sound, (ms^{-1})
D	Level difference, (dB)
D_n	Normalized level difference, (dB)
$D_{n,w}$	Weighted normalized level difference, (dB)
$D_{nT,w}$	Weighted standardised level difference, (dB)
DIN	German Institute for Standardization
dB	Decibel (unweighted)
dB(A)	Decibel (A-weighted)
E	Young's modulus, (Nm^{-2})
EN	European Standard
η	Loss factor, (-)
Fls	Fluctuation Strength, (vacil)
Fls'	Specific fluctuation strength, (vacil)
f	Frequency, (Hz)
Hz	Hertz
ISO	International Organization for Standardization
L	Level, (dB)
L_N	Loudness Level, (phon)
L_{nor}	Normalized loudness level difference, (-)
$L_{nor,w}$	Weighted normalized loudness level difference, (-)

m	Mass, (kg)
m'	Mass per unit area, (kg m^{-2})
N	Loudness, (sone)
N'	Specific Loudness, (sone)
NC	Noise Criterion
NR, NRC	Noise Rating, or Noise Rating Curve
PSD	Power spectral density, (dBm Hz^{-1}; W Hz^{-1})
R	Sound reduction index, (dB) Roughness, (asper)
R_w	Weighted sound reduction index, (dB)
R'	Apparent sound reduction index, (dB) Specific roughness, (asper)
R'_w	Weighted apparent sound reduction index, (dB)
ρ	Density, (kg m^{-3})
S	Sharpness, (acum) Area, (m^{-2})
SPL	Sound pressure level, unweighted, (dB)
STL	Sound Transmission Loss, (dB)
s	Stiffness, (Nm^{-1})
T	Reverberation time, (s)
TL	Transmission loss, (dB)
Ton	Tonality, (tu)
t	Thickness, (m)
τ	Transmission coefficient, (-)
W	Sound power, (dB)
w	Weighting factor, (-)
WHO	World Health Organization

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1 INTRODUCTION

1.1 Research Background

Acoustic comfort is assessed in general by subjective evaluation. It describes a condition that expresses satisfaction with the acoustical environment. This is one of the most important goals of building acoustics engineers.

Tachibana and Lang (2005) stated: "*During the second half of the 20th century, virtually all of the major countries of the world have recognized that environmental and occupational noise are public health problems requiring effective and affordable noise control practices*."

Environmental or occupational noise are not the only reason which could cause health problems, there are also strong indications that also noise from neighbours in apartments causes health problems.

In general rooms for residential purposes, flats and dwelling-houses are supposed to be designed and constructed with the aim to provide reasonable airborne sound insulation (The Building Regulation, 2000). A measure to describe airborne sound insulation is the airborne sound reduction index or the sound level difference both are descriptors defined in standards.

Protection against noise is such an essential requirement, that it has been stated in the European Construction Product directive (Council Directive 89/106/EEC, 1989). In that document six essential requirements are stated of which the fifth is about the sound insulation in buildings: "*The construction works must be designed and built in such a way that noise perceived by the occupants or people nearby is kept down to a level that will not threaten their health and will allow them to sleep, rest and work in satisfactory conditions.*"

A major factor arises from disturbances between dwellings due to audible sounds perceived from neighbour's activities. In the Scottish Government Publication (Noise, 2013) it is noted that: "*Changing lifestyles has altered the way rooms are used in dwellings. Bedrooms are more often used as areas where people spend time watching television, playing computer games and listening to music*". These activities may cause sound which enters the neighbour's area and is unwanted sound. Unwanted sound is commonly called "noise" and can have an impact on people physically as well as psychologically (WHO, 2009). The psychological interaction is primary important in the field of annoyance. Therefore the psychological interaction is the main factor in judging neighbour's noise.

The basic characteristics of a sound field are now known, but so far hardly taken into considerations how these measures are perceived by people. It is however, important to be aware of the fact that limits given in standards and regulations cannot guarantee that no unwanted sound transmission occur (Noise, 2013). Standards and regulations can only provide limits to reduce in general effects from sound levels created from normal domestic activities. They cannot protect from excessive noise from other sources such as inconsiderately played audio systems at high volume or even raised voices (Noise, 2013).

The main body of standards of sound insulation in dwellings are originated since the early 1950s and as shown in the literature (Rasmussen and Rindel, 2005; Neubauer and Scamoni, 2013) in Germany for example the first standard is dated as early as 1938 (DIN 4110, 1938). Meanwhile, living standards have improved significantly. A consequence of this is among others that home entertainment systems and other domestic electrical appliances are extensively used. The quality of sound insulation in buildings is generally described as a single number rating of sound insulation. Many methods have been proposed for single number ratings of partition sound insulation performance. None has been robust enough to be completely satisfactory. Due to raised comfort demands concerning the airborne sound insulation in dwellings, as well as in flats and houses, it is not sufficient to avoid intelligibility listening through walls but to avoid recognition of transmitted sounds in general.

Thus, building acoustic and acoustic comfort inside the building, among other factors concerning building construction, e.g. stability, cost, thermal comfort etc., plays an important role. Since noise is known to cause sleep disturbance (Drucksache, 1999; Muzet, 2007) the negative effects of noise on human health have been widely investigated.

Little data exists on this subject but the LARES-survey (Niemann et al., 2005) and the enHealth report (enHealth, 2004) gives an indication of the proportion of people who are affected by noise. In the results of the LARES-survey in 2003, initiated by the European Housing and Health task force of the world health organisation (WHO), it is recommended to introduce in a more distinct way the subjective related assessment of sound insulation in buildings.

Noise is increasingly becoming a community concern and various surveys have found respondents were concerned about noise generated by neighbours' loud voices, loud appliances and radio, TV, hi-fi (Northwood, 1975; Grimwood et al., 2002; defra, 2006; EPA, 2007). And as Grimwood (1997) affirms in England, e.g., many people are dissatisfied even if their homes meet the intended standard. This may be explained by the fact that regulations present minimum levels of sound insulation, which sometimes might not be enough to satisfy customer's expectations. In objective measurements of the overall response of airborne sound insulation the need is continually felt of a method of interpreting them subjectively.

It is therefore of vital interest to develop a method to judge the intrusive noise in residences which corresponds to the subjective evaluation in order to prevent stress induced health effects. Investigations thus far indicate that the airborne sound insulation measured in accordance with present standards (ISO 16283, 2014) does not correlate well with subjective impression (Joiko et al., 2002; Lang et al., 2007; Neubauer, 2005; Neubauer and Kang, 2011 a, b; Neubauer and Kang, 2014 c). The quality of sound insulation in buildings is generally described as a single number rating of sound insulation (Neubauer, 2004) and has an important bearing on the comfort, health and general amenity of the residents (Langdon et al., 1981; Bradley, 1983; Neubauer, 2005; Ryu and Jeon, 2011). Each country has its own standards of sound insulation in buildings (Rasmussen, 2007), but it is measured in the same way (Lang et al., 2007), that is, a sound level difference is measured and corrected for the influence of sound absorption and external noise in the receiving room. Comparing single number quantities of airborne sound insulation with subjective estimated airborne sound insulation yield frequently serious differences (Vorländer and Thaden, 2000; Joiko et al., 2002). The airborne sound insulation as currently used in standards is not well related to the psychoacoustic facts to describe hearing sensation (Hongisto et al., 2014). It was found in literature that complains are registered even for partitions fulfilling specific requirements on airborne sound insulation (Tonin, 2004; Müllner et al., 2007; Rasmussen and Lang, 2009; Ljunggren et al., 2014). Lowry (1989), for example, reports of a study of newly completed but unoccupied houses who gave poor results and summarized that: “*Over 1200 party walls and about 500 party floors were tested, and over half of the walls failed to meet the Building Research Establishment's recommended standard for the transmission of sound*“.

It is thus necessary to establish a better understanding for airborne sound insulation with means of psychoacoustics.

1.2 Motivation

There is a global demand for a healthy environment. Noise as one of the most contributing factor besides pollution, has been widely accepted as a contributing factor towards health risk (Council Directive 89/106/EEC, 1989).

The Scottish Government Publication (Noise, 2013) states that: "*Airborne sound insulation should be provided where any separating wall or separating floor is formed between areas in different occupation. The intention is however not to prevent all sound from being heard, but to limit noise nuisance by achieving levels of sound insulation that will help to reduce the effects of sound on people in their home. Usually, the purpose of regulations, standards, and guidelines are to limit the transmission of sound to a level that will not threaten the health of occupants from sound transmission emanating from attached buildings and a differently occupied part of the same building. However, the methods to set that margin or limit do not correlate well with subjective expectations or needs. Standards in general however, will not guarantee freedom from unwanted sound transmission. Its aim is to limit the effects from sound levels created from normal domestic activities, but not from excessive noise from other sources such as power tools, audio systems inconsiderately played at high volume or even raised voices*".

On the basis of the findings outlined in the literature (Kranendonk, et al., 1993) it was concluded in the Night Noise Guidelines for Europe (WHO, 2009): "*That the standard of inter-dwelling sound attenuation presently required does not provide sufficient protection to prevent annoyance caused by noise from neighbours.*"

This Guideline (WHO, 2009) also states: "*Since people are less tolerant of the noise their neighbours make at night-time than of their neighbours' evening or daytime noise, it may be* *assumed that much of the annoyance associated with noise from neighbours relates to the influence of such noise on sleep.*"

Furthermore it cited in section 4.8.5 NEIGHBOURHOOD NOISE AND MENTAL HEALTH, of the literature *(Chartered Institute of Environmental Health, 1999)* that: "*Noise from neighbours is the commonest source of noise complaints to local authorities in the United Kingdom.*"

And finally, as Grimwood (1993) pointed out: "*An unwanted sound which is continuous, apparently indefinite, of uncertain cause or source, emotive or frightening or apparently due to thoughtlessness or lack of consideration is most likely to elicit an adverse reaction.*"

Indeed, continued exposure to noise can be very disturbing and/or annoying. It is very well known that continued exposure to noise can also interfere sleep and everyday activities.

As Raw and Oseland (1991) stated: "*In poorly built dwellings, especially apartments, even low intensity noises may be clearly audible through walls, floors, or ceilings.*" This demonstrates the need to operate current buildings more effectively in terms of airborne sound protection between dwellings, flats, and apartments, etc., and for them to be built such that they prevent inhabitants as much as possible. Once the protection is sufficiently increased this should be provided through the application of soundproofing where feasible. It is noticed that the interest of new "soundproofing" buildings as well as for refurbished existing building stock is increased. Nevertheless it has been also noted that, in cases where houses, flats or dwellings have been monitored after occupation, real performance fails to meet expectations (defra. 2006; UBA, 2002; UBA 2013). This *performance gap* results from a combination of factors. Building acoustics prediction is repeatedly unrealistic and poorly considered at the design stage and tends to be considered too positive as a result of trying to meet the noise protection program. Unexpected modifications that occur during the construction phase will affect the expected sound insulation in buildings. These modifications are for example cheaper equipment installations, material changes, and poor build quality. After the building is occupied, noise is generated by the inhabitants not considering the rule of “mutual consideration”.

Finally, as Fothergill (1988) stated: “*One of the main problems in sound insulation is predicting performance. Even nominally identical constructions can provide levels of sound insulation differing by several dB. If no design changes to account for the difference can be found then the cause of variability is usually attributed to workmanship*.”

Furthermore a study by Craik and Steel (1989) of airborne sound transmission through a building has shown that: “*parts of the building which appear to be identical do not have the same acoustic performance. They argued that this difference cannot be explained by differences in the dimensions or material properties, nor by variations in flanking transmission and concluded that the variation, which is approximately 2 dB, is due to workmanship*.”

In the last few years sound protection between dwellings, flats, and apartments, has become a popular topic. With publication of the COST action TU0901 (COST Action TU0901; Neubauer,2015) and the observed increased post occupancy evaluation, new attention has now been given to building acoustic issues in Europe.

However, regardless of the results of previous post occupancy evaluation studies conducted over the last years, recently reported evidence in the literature indicate that the problem still exists (Grimwood et al., 2002; Gerretsen, 2003; Tonin, 2004; EPA, 2007; UBA, 2013; Smith and Mackenzie, 2014). It is needed that a kind of building investment contracting is emerging in the construction industry. It is important that design teams will be held accountable for in-use performance. This would lasting influence the current state of the performance gap. It is, however, likely that designer will need to take more caution creating well-considered design stage sound protection consumption estimates if they are to later ensure sufficient sound protection.

In addition, a severe problem exists with actual performance evidence of sufficient sound insulation, frequently involved in buildings to gain for sustainability rating points, or to portray a certain sound protection image. Performance estimations provided by the manufacturer are repeatedly based on results taken from tests conducted under laboratory conditions. These results are often overestimate the sound protection performance. There is still limited evidence of how sound protection construction are assessed in buildings by the occupants.

Furthermore, both, EN 12354-1 for the prediction as well as EN ISO 717-1 for the calculation are problematic due to the fact that the time dependent information is omitted (Neubauer and Kang, 2011).

1.3 Research Aim and Objectives

This research aims to explore airborne sound insulation as an objective and subjective measure. It studies the application of sound insulation linked with psychoacoustic factors to find an integrated relation of physical and psychoacoustic parameters to describe airborne sound insulation.

This will be approached through the following objectives:

- To review current literature on building acoustic performance with the focus on airborne sound insulation (Chapter 2)
- To explore the unsuitability of conventional standards, in particular, to review the principles of the physical resistance of a sound transmitted through a structure (Chap-

ter 3.1) and to reveal discrepancies of descriptors describing airborne sound insulation (Chapter 3.2)

- To establish a loudness based model (Chapter 4)
- To validate the proposed model, in particular, to explore the influence of sound signals to the airborne sound insulation (Chapter 5.1) and to assess subjectively test signals (Chapter 5.2), and finally to explore the model implementation (Chapter 5.3)

The development of the kind of knowledge that is applicable to real airborne sound insulation and real assessment problems was the underlying objective of this study.

1.4 Research Scope

This research takes a wide approach covering various aspects which may affect building acoustics performance. This methodology allows an overview of the areas of most importance to be assessed. Where it has not been possible to conduct detailed research into specific constructions, plans for future investigation have been suggested.

The modelling process has been done from the point of view of a “designer”. This approach provides useful information on the relevance of model for design. It supports development of practical guidance especially for manufacturers as well as for consultants.

1.5 Thesis Structure

The methods to achieve the objectives for each chapter are described as follows:

Chapter 2, '*Literature Review*', presents a literature review on the development on airborne sound insulation and its rating. Firstly, it covers the reviewing of publications on requirements throughout Europe as well as on surveys on sound protection of residential constructions in Europe and thirdly it discusses occupational noise. Finally, measurement, rating and calculation of airborne sound insulation are reviewed.

Chapter 3, '*Unsuitability of conventional standards*', refers to theoretical definitions on airborne sound insulation and calculating schemes in Europe standards. Furthermore, this chapter brings up loudness and loudness level and discusses frequency weighting in some details and introduces the psychoacoustic measure fluctuation strength. It also describes types of noises and classifies noise types in principal. Lastly, experimental analysis is presented discussion accuracy between theory and measurements concerning airborne sound insulation.

Chapter 4, '*Establishment of a loudness based model* ', introduces the developed new approach to describe airborne sound insulation in terms of a psychoacoustic measure.

Chapter 5, '*Validation and implementation of the loudness based model*', describes experimental results on the characteristics of sound insulation by construction.

Firstly, it introduces the signal types used and depicts the objective and psychoacoustic measures. Followed by subjective assessment tests conducted for differentiating various sound signals.

Finally a series of measurements carried out to examine the airborne sound insulation of a partition to demonstrate the model implementation on site measurements.

Chapter 6, '*Discussions*', refers to the results obtained through theoretical considerations and site measurements. It discusses results in detail and shows the interaction between the obtained objective and subjective measures.

Chapter 7, '*Conclusions*', concludes the thesis, summarising the new findings from the original research. Followed by '*Concluding Remarks and Future Work*', which describes the difference between design prediction and the measured performance. Stating that airborne sound insulation is no longer a kind of "anchor technology" due to an enlarged range of performance options and fulfilment options. Furthermore, recommendations for future work of this thesis are also addressed.

2 LITERATURE REVIEW

This chapter provides an overview of building acoustics performance, with a focus on airborne sound insulation in Europe. It includes a description of current legislative requirements for sound protection in buildings.

A review of the current state of knowledge of the sound protection is given. This focuses on the main area being the potential causes of the problem.

Secondly (see section 2.2), a review of published studies, where actual sound protection performance has been compared to occupational noise, provides a knowledge base of how buildings have to perform in-use.

Thirdly, occupational noise is explored from the literature (see section 2.3). Finally (see section 2.4), the measurement, rating and the calculation of airborne sound insulation are considered.

It is noted that in the United States, the sound transmission class rating is generally used instead of what is preferred in Europe. Since the basic method for the descriptors defining airborne sound insulation is similar, the focus in describing the airborne sound insulation in this research is on the descriptors defined in European standards.

2.1 Requirements in Europe on Airborne Sound Insulation

In this chapter the demands and requirements on airborne sound insulation in Europe is described.

The history of sound protection standardisation in Germany for example, goes far back to before 1938 where "Partitions" had to be heavy at least 450 kg/m² which today, one would say, this is equivalent to an airborne sound insulation of at least R'_w = 54 - 56 dB (Neubauer and Scamoni, 2013).

In the UK as another example, there was no Code of Practice that covered any aspect of sound insulation before 1948, when CP 111 Structural recommendations for loadbearing walls (BS. CP 111. 1948) was published through the good offices of the Ministry of Works – a government department (Haseltine, 2012), which confirmed sound insulation values for building elements. Depending on the size and density of traditional clay brick walls in the UK the range of the airborne sound insulation is of about R'_w = 46 – 50 dB .

Other countries in Europe followed and some still do not have any regulations on airborne sound insulation (Rasmussen & Machimbarrena, 2014).

A literature study by Rasmussen and Rindel (Rasmussen and Rindel, 1996) of a survey in different countries in Europe about noise protection, noise from neighbours, and needs of habitant’s states that many people are annoyed by noise from neighbours and people are annoyed by the fact that their neighbours can hear them. They summarized results for some surveys and stated that for example one-third of the residents feel disturbed by the neighbours.

The prediction models in the European countries are somewhat different in both, the requirements to be met by the constructions and the calculation method.

Also, the quantity used for rating the sound insulation of the constructions is different. Many European countries use standard (EN-ISO) indexes to evaluate the airborne sound insulation between interior spaces.

Kihlman (1995) states: "*The differences between the values and the spaces that are specified in the various regulations are enormous and cannot be easily presented in common tables*." Kihlman (1995) presented first a table showing the indexes used in 11 European Union countries as well as the minimum values for airborne sound insulation between dwellings.

Later on Rasmussen and Rindel (2005) extended the work of Kihlman showing in detail the different concepts and quantities applied in the European countries.

The use of different concepts is also true for other countries in the world. All have their calculations based on single number ratings. None of them take into account the subjective estimation of that single number rating. Guidelines and regulatory sound insulation requirements for row housing, multi storey residential housing, or dwellings exist in Europe in more than 30 countries, however, all having different "protection values" and descriptors as is seen for example in Tab. 2-1.

Table 2-1: Requirements on airborne sound insulations in 30 European countries, taken from (Rasmussen & Machimbarrena, 2014).

Status June 2013		Multi-storey housing	Row housing
Country	Descriptor	Requirements (dB)	Requirements (dB)
Austria	$D_{nT,w}$	≥ 55	≥ 60
Belgium	$D_{nT,w}$	≥ 54	≥ 58
Bulgaria	R'_w	≥ 53	≥ 53
Croatia	R'_w	≥ 52	≥ 52
Czech Rep.	R'_w	≥ 53	≥ 57
Denmark	R'_w	≥ 55	≥ 55
England & Wales	$D_{nT,w} + C_{tr}$	≥ 45	≥ 45
Estonia	R'_w	≥ 55	≥ 55
Finland	R'_w	≥ 55	≥ 55
France	$D_{nT,w} + C_{tr}$	≥ 53	≥ 53
Germany	R'_w	≥ 53	≥ 57
Greece	R'_w	≥ 50	≥ 50
Hungary	$R'_w + C$	≥ 51	≥ 56
Iceland	R'_w	≥ 55	≥ 55
Ireland	$D_{nT,w}$	≥ 53	≥ 53
Italy	R'_w	≥ 50	≥ 50
Latvia	R'_w	≥ 54	≥ 54
Lithuania	$D_{nT,w}$ or R'_w	≥ 55	≥ 55
Netherlands	$R'_w + C$	≥ 52	≥ 52
Norway	R'_w	≥ 55	≥ 55
Poland	$R'_w + C$	≥ 50	≥ 52
Portugal	$D_{nT,w}$	≥ 50	≥ 50
Romania	R'_w	≥ 51	≥ 51
Scotland	$D_{nT,w}$	≥ 56	≥ 56
Serbia	R'_w	≥ 52	≥ 52
Slovakia	R'_w or $D_{nT,w}$	≥ 53	≥ 57
Slovenia	R'_w	≥ 52	≥ 52
Spain	$D_{nT,A}$ ($\approx D_{nT,w} + C$)	≥ 50	≥ 50
Sweden	$R'_w + C_{50\text{-}3150}$	≥ 53	≥ 53
Switzerland	$D_{nT,w} + C$	≥ 52	≥ 55

From this table it can be seen that requirements among these European countries differ quite a lot. However, even though a consensus does not exist in Europe about the requirements, terms used, as well as the frequency range to which they are applied, one does exist for the need for improvement (Rasmussen and Rindel, 2005). This comes from the fact that even though vast improvements have been made, up until the 1990's the number of people annoyed by their neighbour's still remained high, i.e. around 15%-20% (Gerretsen, 2003). This can also be seen from the continuous introduction of new terms such as the C_{tr} weighting that was introduced in the United Kingdom in 2003 (Smith and Mackenzie, 2014).

From Tab. 2-1 it is further observed that quite different regulations exist. Table 2-2 summarizes the countries which have the same descriptor to describe airborne sound insulation.

Table 2-2: Summary of descriptors used in 30 European countries for airborne sound insulation.

Airborne sound	
No. of countries	Descriptor
16	R'_w
3	$R'_w + C$
1	$R'_w + C_{50\text{-}3150}$
6	$D_{nt,w}$
2	$D_{nT,w} + C$
1	$D_{nT,A}$ ($\approx D_{nT,w} + C$)
1	$D_{nT,w} + C_{tr}$

In the publication: "*Volume I*" of the COST-Action TU0901 (Rasmussen & Machimbarrena, 2014) the main findings from comparison of the requirements in airborne sound insulation in 35 European countries are shown.

For airborne sound insulation this is summarised in Tab. 2-3.

Table 2-3: Summary of the main findings from comparison about requirements in 35 countries in Europe, 2013. Ref. (Rasmussen & Machimbarrena, 2014).

Airborne sound insulation
7 descriptors + variants/recommendations
For multi-storey housing differences up to 6 dB
For row housing differences up to 10 dB
8 countries apply *C*-terms
Low-frequency (down to 50 Hz) *C*-terms applied only in Sweden
The strictest requirements for are found in Scotland and Austria for multi-storey and
5 countries have no requirements

It is also stated in the publication: "*Volume I*" of the COST-Action TU0901, that: "*In regulatory terms, a significant challenge is that for some types of lightweight constructions, the subjective sound insulation is ranked lower than for a heavy construction with the same objective sound insulation. Regulatory requirements are objective, and the same requirements should be applicable for all types of housing constructions and materials. Thus, an important research task is to develop new objective descriptors (evaluation methods) correlating with the subjective evaluation for all types of constructions. – In Norway, a survey (Barlindhaug, 2008) about satisfaction with newly built homes (2005) has been carried out in 2007. In general, people are satisfied (about 80%, 10% dissatisfied). Least satisfaction (17% dissatisfied) is found with sound insulation, especially for 2-storey housing (27% dissatisfied). According to (Hveem, 2010), the reason is likely to be light-weight constructions applied for such housing*".

Thus, as seen in Tab. 2-3 there are differences in airborne sound insulation requirements in multi-storey housing up to 6 dB and up to 10 dB for row housing which is certainly "heard" in subjective regards and this difference is not justifiable with "construction restrictions".

Austria and Scotland, for instance, are good examples that high airborne sound insulation can be achieved even for lightweight constructions (Smith et al., 2001; Lang, 2006).

Since the very beginning of the specifications of sound insulation objectives in Europe, changes in the living style and living standards are observed. However, as Gerretsen (2003) stated, acoustic requirements are essentially still the same as fifty years ago.

As a subjective experience of noise stress can lead to regulation health problems, as reported, for example, in (Niemann et. al., 2005; Lee et al., 2010; Fyhri and Aasvang, 2010; Muzet, 2007), it is important that a more specific requirement be established to quantify sound insulation to safeguard occupants from possible health effects.

In general acoustical regulations deal with various areas of the human activities. Improvements in acoustic regulations are noticed in many countries. That is, they are more demanding and closer to inhabitants' expectations but these regulations also imply increasing costs for construction. The European countries in general differ in their approach to the Building Acoustics Regulations. It is therefore difficult to compare results and solutions, mostly because the different regulations are not entirely equivalent, i.e. comparable (Rasmussen, 2010).

However, there is a common purpose which is a cost effective goal between a healthy and comfortable living environment and the expenses to build such a building. The acoustical regulations deal as Carvalho and Faria (1998) have shown, at least with the following fields:

- "*Health: noise power limitations to equipment in several areas of work;*
- *Building acoustics: minimum performance levels for insulation in many types of buildings;*
- *Urban acoustics: definition of quiet and noisy places;*
- *Traffic: limitations to noise produced by vehicles;*
- *Environment: limitation of noise levels produced by "noisy activities"*."

2.2 Sound Protection of Residential Constructions

In the literature (UAB, 2002, UBA 2013) results of environmental surveys in several European countries have reported that noise from neighbours is the second most common source of noise annoyance behind the road traffic noise interference.

Austria conducted a survey in 2003 from which it is reported that 7.7% are disturbed strongly or very strongly due to noise from neighbours as the cause of the disruption. In a previous survey in 1985 the disturbance was reported to be 12%. Overall people disturbed by noise (29.1% of the respondents), 10.4% named the noise from the neighbouring apartments as a cause of disturbance (Lang et al., 2006).

In Germany a representative survey in 2004 (Ortscheid et al., 2006) revealed that from 42.7% in total 17.3% are medium, strong or bothered most by the noise from neighbours. The data show that 2/3 of respondents who have direct neighbours, 16% hear noise from their housing activities well or very well.

In the United Kingdom the building research establishment (BRE) undertook during the years 1999 - 2001 a measurement based survey of environmental noise levels and a social survey of population attitudes to environmental noise (BRE, 2002). One result was that 58% claimed to hear the noise of neighbours in their apartment.

In France a survey was conducted between the years 1998 to 2004 and it have been reported the interference by neighbouring noise (Le Jeannic et al., 2005). 41.2% of all households were disturbed by noise in total and 19.6% by neighbouring noise.

In the Netherlands it was found in a study (van Dongen, 2001), that about 75% of the noise from the neighbouring apartments can be heard, in 40% daily. In approximately 1/3 of all households this sound was annoying, and for 13% very disturbing. 95% said that they look at their own behaviour to avoid disturbing the neighbour's noise.

In a representative survey conducted in the Switzerland by Lorenz (2000) public perception of noise and disturbance by noise was on the general question of the status of the noise problem in a general way and a personal perspective on a scale of 1 to 6 (1 = not concerned at all, 6 = concerns very much). The neighbourhood noise was rated with 2.5. People, who are not satisfied with their home, clearly promote the environmental impact through the neighbourhood noise (3.1) while people who are satisfied with their home rated (2.4).

2.3 Occupational Noise

Occupational noise is often related to music where the question arises if heard music in an adjacent dwelling is accepted or not. Is for example: classical music or rap, hip-hop, or grunge music, noise or music? The answer depends on the perspective of the affected. For the study of occupational exposure to noise it is common to consider the physical characteristics of noise, however, it is also important to consider the way the human ear responds to it. The problem of assessing "*sound*" is complex due to the hearing system.

It is general knowledge that perceptions vary from person to person. Different people perceive different things about the same situation. Green (2014) states: "*Psychologists talk mainly about two different kinds of threshold for sensation and perception: the absolute threshold and the difference threshold. The absolute threshold, also known as the detection threshold, refers to the weakest possible stimulus that a person can still perceive.*"

As Lawless and Heymann (2010) mentioned: “*One of the earliest characteristics of human sensory function to be measured was the absolute threshold. The absolute or detection threshold was seen as an energy level below which no sensation would be produced by a stimulus and above which a sensation would reach consciousness*”.

The first systematic studies of sensory thresholds were, as Norwich (1993) conclude, conducted by physiologist Ernst Heinrich Weber. Norwich summarized: “*Weber's experiments were designed to determine sensory thresholds, of which there are two types:*

- *Absolute threshold -- the minimum intensity of a stimulus that one can detect*
- *Difference threshold -- the minimum difference in intensity between two stimuli that one can detect*

Weber defined the absolute threshold as the intensity at which the stimulus was detected on 50% of trials.”

These trials or tests are widely known as signal detection analysis (Norwich, 1993).

Hearing a voice is a sensation while recognizing it is a perception. This distinction was clarified by Norwich (1993) with an example: “*Sensation is passively receiving information through sensory inputs, and perception is interpreting this information.*”

Peoples response to the information is therefore included in perception. Norwich (1993) stated: “*We can think of perception as a process where we take in sensory information from our environment and use that information in order to interact with our environment*.”

Therefore, perception is the possibility to convert sensory information into something meaningful. Hence, in assessing a sound in a room, it is vital to distinguish between perception and sensation.

Furthermore, what is a very important aspect of sound assessment is the awareness of the event of an intruding sound which has to be assessed. That means the degree of interference of disturbance is a measure of nuisance. The term “*nuisance*” by the way, traces back to the Latin word “*nocere*”, which means nuisance. That is why noise can be defined as "disagreeable or undesired sound", or “wanted or unwanted sound”.

Since in general sound and noise constitute the same physical characteristics, it is the differentiation which counts and this is greatly subjective. The human ear response to sound both on the sound frequency and to the sound pressure level (Hansen, 2010).

In the literature it is found, that the range of audible sound is approximately from 20 Hz to 20,000 Hz, that is 10 octaves. The range covered by speech sounds is from about 100 Hz up to 7,000 Hz (Zwicker and Fastl, 1999; Moore, 2004).

Fasold (Fasold et al., 1987) published a frequency response of medium sound pressure level of speech for male and female.

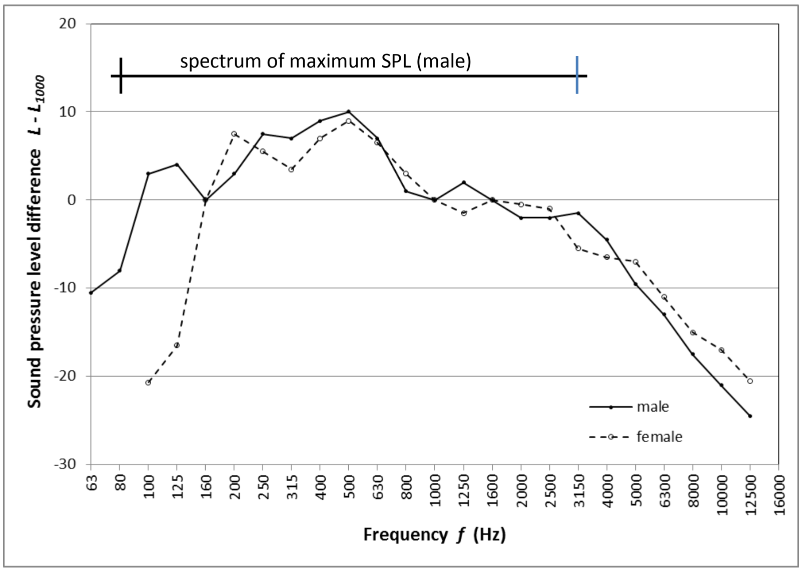


Figure 2-1: Frequency response of medium sound pressure level of speech (Fasold et al., 1987).

In Fig. 2-1 the frequency responses of the medium one-third-octave band centre frequency of a normal conversation, relative to a mid-frequency of 1k Hz is depicted. It is seen that the voice of the man is about one octave lower than of the female. Fasold (1987) identified the spectrum of the maximum sound pressure level: "*in a frequency region of about 80 Hz for a male, and 160 Hz for a female, respectively, and 3,000 Hz*."

In that frequency region are the basic tones and the formant zones of the vocals and of the voiced consonants. Fasold (1987) stated also, that singing produces a similar frequency response of medium sound pressure level as for speech.

The approximated borders of music and speech signals in octave bands are shown in Fig. 2-2. The outer limit (solid line) shows the full range of audible sound for young listeners with normal hearing. It is seen in Fig. 2-2 that "Music" occupies a limited range, especially at higher frequencies and "Speech" covers even a narrower area or limit range.

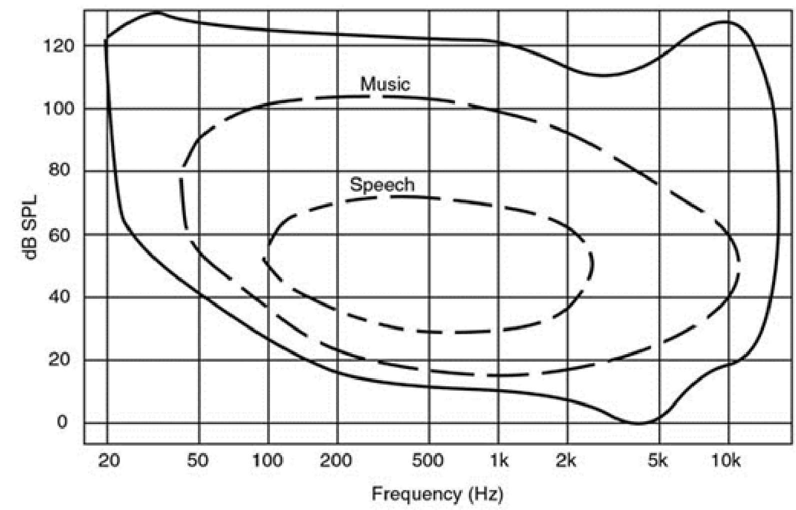


Figure 2-2: Approximate limits of bandwidth and dynamic range of music and speech signals Eargle and Foreman, 2015).

Figure 2-3 displays the cumulative speech signal of a normal adult male speech power spectrum in octaves. It is seen that the speech spectrum shows maximum value at a frequency of about 250 Hz. In the frequency range above 1k Hz the level falls off per octave roughly by 6 dB.

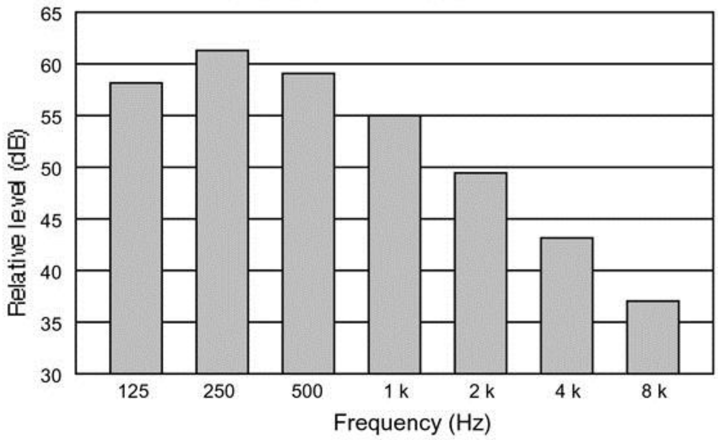


Figure 2-3: Long-term speech spectrum of a normal adult male (Eargle and Foreman, 2015).

In Fig. 2-4 are the long-term octave-wide power spectra of rock music and classical music shown. It is noted that at middle and higher frequencies the spectrum of classical music is comparable to that of speech (see Fig. 2-3).

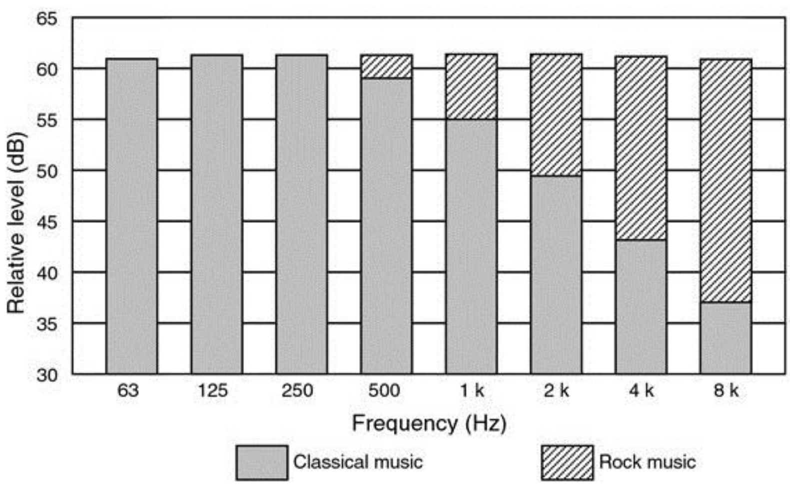


Figure 2-4: Long-term speech spectrum of classical and rock music (Eargle and Foreman, 2015).

The use of sound producing equipment such as audio and television has been increase in an enormous way in in the last century since acoustic regulations are established (Noise, 2013).

Furthermore, music nowadays is often more bass orientated and is played at higher volumes and hence it can create a disturbance to others. Occupational noise can be annoying if sound insulation is inadequate because noise from the neighbours can restrict the quality of living.

To increase the resistance of building elements to sound transmission in an adequate way it is especially important to know the spectrum of the source sound. The knowledge of the interaction of objective and subjective measure is of vital interest. Especially the limitation of noise nuisance will help inhabitants adequately to live in their homes. This is an optimization process between the objective need and the subjective demand.

Fasold (1959) published at the third International Congress on Acoustics noise spectra from measured mean disturbing dwelling noises and concluded in connection with the equal-loudness contours (ref. to Chapter 3.1.3, Fig. 3-9) and the loudness calculations made according to Zwicker (1958) and Stevens (1956) a most effective sound insulation over frequency.

The referred noise spectra of the measured mean disturbing dwelling noises are depicted as a copy in Fig. 2-5 of the original work from Fasold.

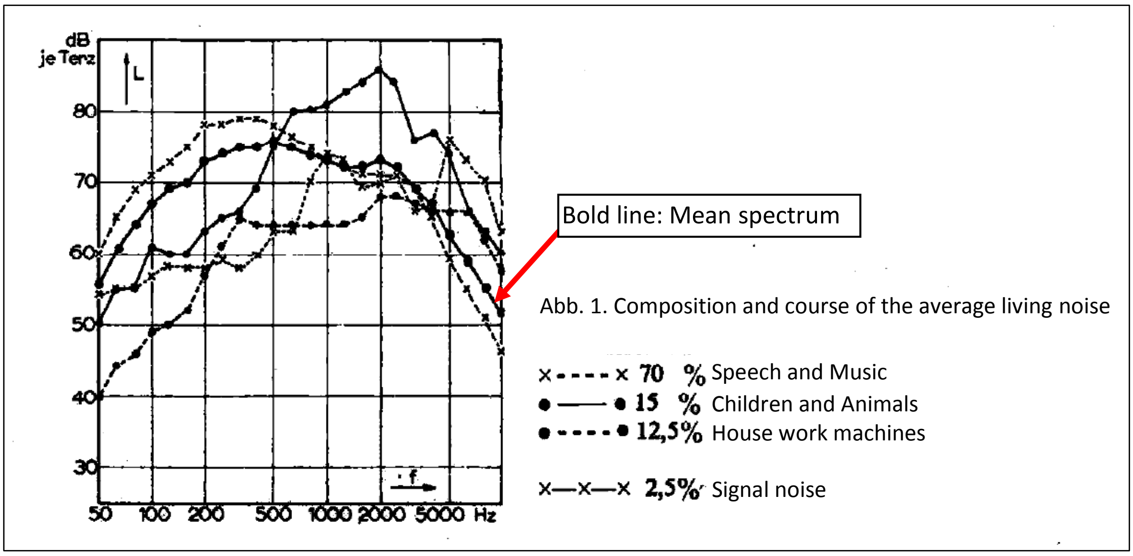


Figure 2-5: Average residential noise spectra for 4 groups: speech and music, children and animal noise, and noises from house work machines (Fasold, 1959). (NB: description of the graph is translated from German to English)

A similar approach used by Lawrence (1969), however in order to find answers of his formulated questions about finding an appropriate sound insulating material or system to reduce the transmission of sound in an required manner. The first question Lawrence (1969) asked was: "*What is an acceptable noise level inside a room and second, what is the nature of the sound that has to be reduced.*" To answer these questions Lawrence (1969) referred to Fig. 2-6 which is shown below. He stated: "*that most research into noise sources in buildings has been done in residential buildings and offices*". Social surveys revealed that prime sources of disturbing sounds in multi-storey residential buildings are radio, TV, and conversation (Lawrence, 1969; Northwood, 1975).It is pointed out that Fasold (1959) has reported ten years before that: "*Most important disturbing sound sources in today's homes are radio and television sets.*"

He stated additionally, that the sound level of a loud radio is of about 85 DIN-phon which is about 85 dB(A). Another example of measured "household" noise is shown below in Fig. 2-6 (from ref. Lawrence, 1969).

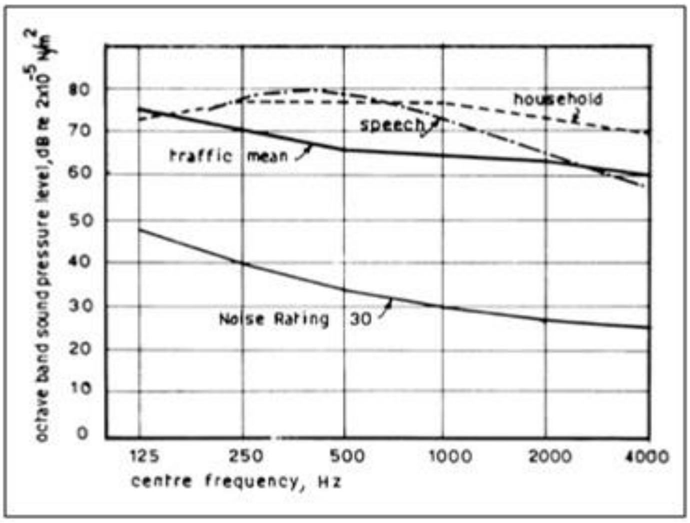


Figure 2-6: Typical spectrum levels of standard household noise, conversational speech, and road traffic, respectively, compared with an acceptable background noise of Noise Rating 30 (Lawrence, 1969).

A publication of another "household noise" was presented by Northwood (1962) which is shown in Fig. 2-7.

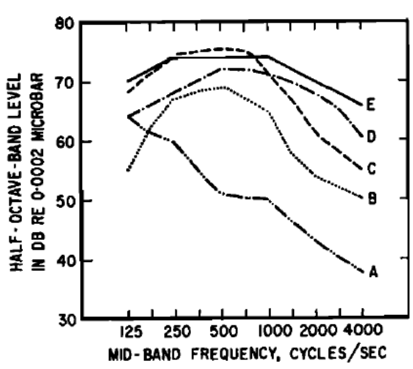


FIG. 4. Half-octave-band levels of typical household noises. Curve A—room air-conditioner, Curve B—vacuum cleaner, Curve C—normal speech (levels exceeded by 1% of speech peaks), Curve D—radio, television (peak levels, speech and music), Curve E—assumed "standard-household noise."

Figure 2-7: Half-octave band spectra for a few typical domestic noises (Northwood, 1962).

Figure 2-7 shows half-octave band spectra for a few typical domestic noises published by Northwood (1962). He stated that: “*The trend in domestic appliances is toward control of the high-frequency components of noise, so that low- and medium-frequency component predominates in the residual noise. Speech, radio, and television noises are broadly peaked in the middle-frequency range. Speech intelligibility as distinct from power, involves a slightly higher frequency range extending well beyond 4,000 cycles but this is irrelevant for dwelling separation since the transmission loss should be substantially greater than the amount required merely to reduce intelligibility. Musical instruments and high-fidelity record players will extend the range, especially toward the lower frequencies. Noting from the surveys the special importance of radio, television and speech noises it appears that one might consider a "standard household noise" spectrum flat from 250 to 1,000 cps and diminishing by 4 to 6 dB per octave below and above this frequency.*”

The spectrum levels from different sources show often as expected great variations. However, in Fig. 2-6 the dotted line labelled “household” may characterise spectrum sound pressure levels of many airborne domestic noises, including television and radio.

Comparing the figures above showing the spectra for “household sounds” as depicted in Figs. 2-5, 2-6, and 2-7, respectively, it is seen that a maximum occurs at about 500 Hz.

On the other hand, Lawrence (1969) stated: “*That in an office the chief source of annoyance is the transmission of intelligible speech. Intelligibility depends on the speech levels transmitted relative to the masking or background noise level in the listening room. Speech levels in the source room depend on the type of conversation and the size of the room. The most important frequencies for intelligibility are from 1,000 Hz to 4,000 Hz.*“

It is seen in Fig. 2-5 as reported by Fasold (1959) that noise from children and animals have maximum level at a frequency range of 2,000 Hz. There are several other publications reporting sound levels of living activities. One example is the Austrian standard ÖNORM S 5012 (ÖNORM, 2012) which provides sound levels produced by living activities.

In Tab. 2-4 some examples are given. The frequency content is assumed to be for conversation and for music like pink noise. However, as shown later this is questionable and it is demonstrated in this work that different spectra will be judged differently compared to pink noise. Evidence is given in chapter 5.2.

Table 2-4: Sound levels of activities in living rooms, (ÖNORM, 2012)

Room	Sound source	L_{eq}	L_{max}
75 m³ living room, with normal furnishing	Conversation with guests, 6 persons Talking with normal voice	73 dB(A)	82 dB(A)
	Lively conversation with laughter	78 dB(A)	87 dB(A)
	Music played at home 1 violin or similar instrument	78 dB(A)	86 dB(A)
100 m³ living room, with normal furnishing	Music played at home Ensemble with 6 instruments	91 dB(A)	98 dB(A)

2.4 Measurement, Rating and Calculation of Airborne Sound Insulation

In this section the standardized methods of measuring, rating and calculating the airborne sound insulation are described.

2.4.1 Measurement

Standardised procedures for measuring the sound insulation of various structures exists in both laboratory and field environments.

The measurement of sound transmission through a partition in building acoustics test facilities is described in ISO 10140 part 2 - "Laboratory measurement of sound insulation of building elements" (ISO 10140-2, 2010).

According to ISO 10140-2, the sound power transmitted into the receiving room can be obtained by determining the sound energy prevailing in the receiving room under steady state conditions. This is done by determining the average sound pressure in the room from pressure measurements in numerous room positions.

The reverberation time of the room is also measured. The absorbed power is determined based on the reverberation time and the energy present, which equals the transmitted power. This method is usually referred to as the conventional method.

In real buildings, the internationally standardised method is provided in ISO 16283-1 (ISO 16283, 2014). This standard specifies procedures to determine the airborne sound insulation between spaces in a building using sound pressure measurements. It requires that one room be chosen as the source room that will contain the loudspeaker and another room that is the receiving room.

The sound insulation is assessed in terms of the apparent sound reduction index R' or the standardised level difference D_{nT}, and the results are weighted and expressed as a single-number quantity, e.g., R'_w, respectively, $D_{nT,w}$, in accordance with ISO 717-1 (ISO 717, 2013). The primed symbol of the apparent sound reduction index indicates a value obtained in the presence of flanking transmission.

The equations for R'_w and $D_{nT,w}$ will be briefly addressed below for clarification reasons but will be again discussed in detail in section 3.1.

The apparent sound reduction index is

$$R'_w = L_S - L_R + 10 \log (S/A) \text{ dB} \quad (2\text{-}1)$$

and the weighted standardised level difference is

$$D_{n,T} = L_S - L_R + 10 \log (T/T_0) \text{ dB} \quad (2\text{-}2)$$

where

L_S and L_R are the average sound pressure levels in the source and receiving room, respectively, S is the area of the test specimen in m² and A is the room absorption area of the receiving room in m². T is the reverberation time in s in the receiving room and T_0 is the reference reverberation time in s, (T_0 = 0.5 s).

The measured level difference is the basic value for determining a descriptor of airborne sound insulation. The most basic index is consequently the weighted level difference D_w. This is an integer value obtained from the frequency-dependent values of the measured sound pressure levels characterising the acoustical performance. This procedure is a standardised method specified in ISO 717-1. In the standard, a set of reference values is provided that has to be used for comparison with measurement results and a set of sound spectra in one-third-octave bands to calculate the spectrum adaptation terms. These frequency-dependent values are provided for reference in Appendix I and II, respectively.

In 2012, a replacement for ISO 717-1, designated as ISO 16717-1 (ISO 16717, 2012), was proposed. It included changes to the frequency range included in the single-number ratings (Mahn and Pearse, 2012; Masovic et. al. 2013). However, no evaluation has been introduced into the proposed new standard that classifies hearing sensation (Neubauer and Kang, 2013 b). Due to resistance from some countries, this proposal was withdrawn by ISO in 2014.

To determine airborne sound insulation, a standard test with broadband noise signals as a source signal is, according to international standards, usually used.

In reality, however, music sounds from neighbours are often said to be a prime cause of annoyance and complaints (Park and Bradley, 2009). Currently, according to present standards, the influence of noise is described primarily by the *A*-weighted equivalent continuous sound pressure level ($L_{A,eq}$). This measure, however, does not give enough consideration to the subjective perception and evaluation of sound (St. Pierre and Maguire, 2004; Leventhall, 2004; Parmanen, 2007) and is not a satisfactory descriptor of a sound event because it cannot describe many signal characteristics, such as time fluctuations (Wang et al., 2013).

Furthermore, as shown in (Yifan et al., 2008), an *A*-weighted level is not suitable to assess low-frequency noise events (Leventhall, 2004).

The time fluctuations of a signal can be captured, for example, by psychoacoustic parameters, including sharpness, roughness, tonality, and fluctuation strength. The investigations thus far indicate that airborne sound insulation measured in accordance with former and present standards does not correlate well with subjective impressions (Joiko et al., 2002; Lang, 2007). The results in the literature suggest that sound level differences would correlate best with subjective responses (Bradley, 1983). However, as will be demonstrated in this work, a sound level difference does not differentiate well with different sound sources with different spectra.

In the meantime, it has been reported that loudness combined with roughness describes the correlation with the subjective estimation of noise-induced discomfort better than the *A*-weighted sound level (Raggam, 2007).

Moreover, as Jeon et al. (Jeon et al., 2010; Ryu et al., 2011) noted, subjective response to noises, such as annoyance, depend upon the type of noise.

NB: Because this research focuses on the loudness level of the receiving room related to the sound reduction index *R*, none of the other quantities to describe airborne sound insulation are further discussed in detail. It is, however noted that all other descriptors to describe airborne sound insulation are connected in one way or another with the *R*-value.

To summarise, the procedure of the standard test to determine the airborne sound insulation properties of a structure is to measure a sound level difference. This is done by placing the structure, material, or element which has to be tested between two reverberant rooms. Each room is equipped with a microphone. In one of these rooms a sound source is installed. This room is usually called source room. The other room is called receiving room. In both rooms the sound pressure level is measured after turning on the sound source. The measurement is carried out using bandwidths of one-third octaves in the frequency range from at least 100 Hz to 3,150 Hz. The measured sound level difference is equal to the airborne sound insulation of the structure, taking into account the area of the dividing structure, partition or element, and the sound absorption in the receiving room.

Taking into account the sound absorption in the receiving room and the area of the test partition makes the values of airborne sound insulation independent of the test facility.

The airborne sound insulation is then a function of the structural parameters only. It describes a basic acoustic property. The techniques for measuring airborne sound insulation are originated to provide full data on the acoustical performance of structures as a function of frequency. This information is important to acousticians or acoustic specialists.

A detailed calculation on the estimated sound insulation in buildings is essential to forecast the acoustical performance of a structure, partition or even a building. However, the detailed data are often confusing to the non-acoustical specialist. For example, Architects who have the task of designing the building are sometimes overwhelmed with to detailed information on the sound insulation.

To simplify this problem, several methods have been suggested to characterise the airborne sound insulation of a structure in terms of a single number. Such methods can be applied as Sharp et al. (2013) summarized to:

- "*rank-order structures in terms of acoustic performance*
- *allow for simplified calculations of noise reduction, such as in a design guide*
- *develop a design optimisation procedure that selects the combination of components that achieve a given noise reduction at minimum cost.*"

The use of a grading curve is one of the method. It specifies the airborne sound insulation required in each one-third octave band. Against this frequency depending airborne sound insulation the measured values for a given structure are compared.

Grading curves can be used in different ways. It can be used as a requirement for structures in buildings, or to give a ranking of one structure against another. Because it would be unreasonable to categorise between two structures in a very rigours way, i. e. if for example the airborne sound insulation value differ by less than about two decibels in a single frequency band, the grading system or procedure tolerate some deviations below the grading curve.

In order to have a tool in building design several grading curves have been developed or suggested. All grading curves have been designed in a similar way taking the difference between typical source levels in buildings and suitable criteria to ensure some acoustical quality in the rooms. Yaniv and Flynn (1978) published a comprehensive review relating different grading curves. They conclude in their publication that: "*the data of subjective responses used to establish the requirements for sound levels in dwellings is extremely variable*." The consequences of that was a development of a number of grading curves. However, the designed grading curves differ at some frequencies by up to 10 dB (Yaniv and Flynn, 1978). These differences, as Yaniv and Flynn (1978) argued, are due to the lack of a comprehensive database on subjective response. Consequently, the concept of grading curves is not practical for assessments to be made on the importance of these differences.

Furthermore, Yaniv and Flynn (1978) stated: "*that the shape of the grading curve is dependent on the typical source spectrum used for the calculations. As a result, there is considerable uncertainty as to the validity of current grading procedures.*"

In the European countries, the standard grading procedure for the airborne sound insulation of building structures was originally given in ISO 140-4 (ISO 140, 1998). The procedure described was actually intended for application to data measured in the laboratory for ranking reasons to assess the potential performance of structures. However, the same grading curve is also applied for in-situ measurements, i.e. field measurements, to describe transmission loss between rooms.

2.4.2 Rating

Perhaps the most extensive research to find a suitable reference curve, at least in Europe, was carried out by Fasold (1959). His findings included an increase in the reference curve at mid-frequencies in the range of 200 Hz-800 Hz. He concluded that in order to ensure a most effective sound insulation curve, it was necessary to increase the requirement for airborne sound insulation.

Lawrence (1969) defined what a rating system should be able to fulfil: "*Rating systems for airborne sound attenuation must take into account the sensitivity of the human ear to sounds of different frequencies as well as the typical spectra of incident noises. Some allowance for experimental and constructional errors must be made and the typical allowable deviations from grading curves serve this purpose. However, allowable deficiencies should be closely related to the subjective acceptance of increased sound transmission at certain bandwidths. The derivation of some of the grading curves in use is important and they should not be indiscriminately applied to all situations. The ideal grading system is one which invariably selects a satisfactory wall or floor for a particular situation and which also invariably rejects one that will not be satisfactory in practice.*" Since that time, not much has changed.

Most measurements of airborne sound insulation, whether laboratory or field, are conducted over a range of frequencies to obtain a detailed picture of performance. Commonly there are 16 one-third octave bands measured from 100 Hz to 3,150 Hz.

Currently, a tendency is observed to measure airborne sound insulation in an extended frequency range from 50 Hz up to 5,000 Hz. Such an extended range can be problematic for assessment reasons. It is particularly unsuitable for comparing the performance of building products or product data related to sound insulation. A single-number rating is therefore more appealing and tempting. For this purpose a single-figure rating is required. This includes also the necessity for single-number ratings for dwellings outlined in the building regulations.

In order to condense the frequency depending sound reduction index at all sixteen discrete frequencies to a single value there exists numerous methods. An obvious method would be to take the arithmetic mean of all frequency depending values. A drawback is, however that an arithmetic mean equalizes outliners, that is for example, very high levels of sound insulation at one or more frequencies can compensation poor performance at other frequencies. This problem is called the “arithmetic mean problem”.

A commonly applied method to avoid this “arithmetic mean problem” is to compare the measured results with a reference curve. The procedures for deriving the values of the sound reduction index (R), the weighted sound reduction index (R_w), the spectrum adaptation term for A-weighted pink noise (C), and the spectrum adaptation term for A-weighted urban traffic noise (C_{tr}) are specified in ISO 10140 part 2 and 4, and ISO 717-1, respective. The first international standard for rating sound insulation of dwellings was an ISO recommendation, ISO/R 717 (ISO 717, 1968), which was based on extensive investigations by, e.g., Gösele (1965), Fasold (1965), and other researchers supporting field measurements according to ISO/R 140 (ISO 140, 1960).

The reference curve is defined in ISO 717-1 (ISO717, 2013). This curve is based on the relative human perception of different frequencies of sound.

Only those sound insulation values are considered in that rating that fall short of the reference curve. This method ensure that so-called “outliners”, i.e. very good results in one or two frequency bands, have not as much impact to the single-figure value. The calculation scheme to obtain a single-figure value of the airborne sound insulation is shown graphically in Fig. 2-8.

The reference curve is moved towards the measured curve until the sum of the positive deviations is less than or equal to 32 dB but as close as possible to 32 dB. The sum of the differences is denoted by *S* and given in Eq. (2-1).

$$S = \sum_{i, R_i < R_{ref,i}} R_i - R_{ref,i} \quad \leq 32\ dB \qquad (2-1)$$

The value of the shifted reference curve at the one-third octave band centre frequency of 500 Hz is then taken as the single numerical value of the weighted sound reduction index R_w. Figure 2-8 shows this graphical method and defines the used parameters of Eq. (2-1).

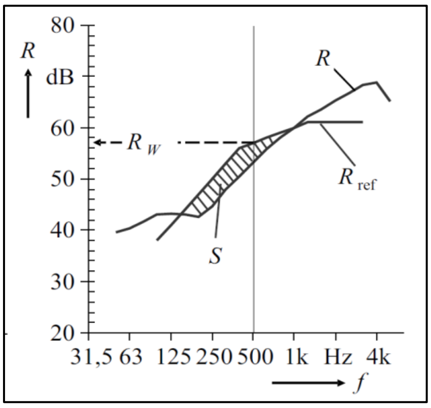


Figure 2-8: Description of the calculation of the weighted sound reduction (Wittstock, 2007).

The routine used for calculating a single value of the airborne sound insulation according to ISO 717 yields the following single-figure values:

- Standardized weighted level difference $D_{nT,w}$
- Weighted sound reduction R_w

The standardised method is an assessment of airborne sound insulation that takes into account the dependence of sound insulation on the incident spectrum. In fact, ISO 717-1 includes two basic spectrum adaptation terms, *C* and $C_{tr,}$ concerning the conventional measurement frequency range. In order to determine the weighted value of airborne sound insulation ISO 717-1 provides a rating method to obtain a single number using a standard reference curve. In annex A of ISO 717-1 it is indicated that the spectrum adaptation terms *C* and C_{tr} can also be evaluated to take into account different source spectra. *C* is supposed to be an *A*-weighted pink noise spectrum, whereas C_{tr} is meant to be an *A*-weighted urban traffic noise spectrum. In order to take into account low-frequency noise C_{tr} may be added to $D_{nT,w}$ or R_w. The problem with the rating, however, remains regarding whether the spectrum adaptation terms are used because it does just reduce the single numerical value of the airborne sound insulation. This performance is best illustrated in Fig. 2-9, where the calculated sound reduction index R_w of a single solid wall in concrete with successively increased thickness is depicted over frequency. The calculation method is discussed in the next chapter and is therefore not further described.

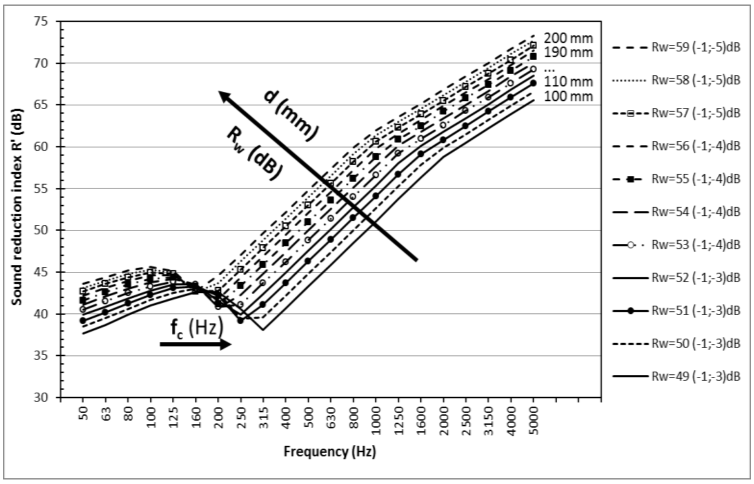


Figure 2-9: Computed sound reduction index for a concrete wall with varying thickness.

The computed sound reduction index R_w of the investigated structures, as shown in Fig. 2-9, are obtained using the software tool INSUL v8.0 (INSUL, 2014). Figure 2-9 shows that with increasing thickness, the sound reduction index rises; however, the spectrum adaptation term C is constant -1 for all thickness, and the spectrum adaptation term C_{tr} is constant -5 dB for all thickness above 174 mm concrete. A reduction of the R_w-value with a constant number does, however, not indicate any subjective impression. There are several conventions for evaluating sound insulation in buildings. There are also several legal building regulation requirements for sound insulation in different countries. All of them claim that the assessment of transmitted sound is adequately well defined in existing regulations. Furthermore, it is not likely that people make complaints about annoying sounds from neighbours near the limit value given in regulations. Opposing to this, Poulsen and Mortensen (2002) argued: "*There is an obvious need for investigations where the subjective annoyance due to typical examples of airborne sound insulation is compared to different objective measures of the sound insulation of the same noises. There are several different features of the different assessment methods presently in use, and the corresponding limits or criteria values differ. The fundamental assumptions for the assessment methods are, however, largely the same.*"

There is a practical need to estimate the quality of the real acoustical comfort of dwellings more accurately. This corresponds to the research tendency in sound quality and in soundscape, acoustic comfort, and psychoacoustics (Vorländer and Thaden, 2000; Parmanen, 2001; Stefaniw, 2001; Kortchmar et al., 2001; Bradley, 2001; Joiko et al., 2002; Bodden, 2004).

In numerous European countries, social surveys have shown that inhabitants of multifamily dwellings are considerably annoyed by noise from their neighbours' activities (Grimwood et al., 2002; defra, 2006; EPA, 2007; Rasmussen and Lang, 2009).

Rasmussen and Lang (2009) noted that: “*neighbours' activities is the second most frequently mentioned noise source after road traffic, far more frequent than railways or air traffic*”. That is why airborne sound insulation is an important factor and mandatory to ensure a healthy living environment in buildings.

The quality of airborne sound insulation in buildings described as a single-number rating of sound insulation in terms of a weighted apparent sound reduction index R'_w is, however, inadequate and requires improvement because of the significant difference between the standard rating of sound insulation and its subjective assessment (Roos et al., 2011). Various investigations have been published that rate airborne sound insulation with respect to its correlation with subjective ratings of sound insulation. Vian et al. (1983), for example, related subjective ratings of sound insulation to an *A*-weighted level difference and found that a statistically significant correlation was observed between annoyance and the A-weighted level difference ratings using a source with bandlimited pink noise (125 Hz - 4k Hz) whereas using a broadband pink noise (40 Hz - 10k Hz) no correlation was observed.

Tachibana et al. (1988) on the other hand investigated the loudness of sounds transmitted through walls and found that the arithmetic mean value of sound pressure level in one octave bands from 63 Hz to 4k Hz is a proper measure for the assessment of the loudness of sounds transmitted through walls.

Park et al. (2007) published results concerning sound insulation ratings of the intelligibility of transmitted speech. He concluded that a R_w-rating is not very accurate predictor of the intelligibility of speech transmitted through walls.

It has to be mentioned that there is another rating scheme that is described as, noise rating levels, or NR level curves. This rating scheme was developed by the International Organization for Standardization (ISO/R 1996:1971 withdrawn). It specifies an indoor acoustic environment for different requirements of hearing, speech and annoyance in different applications (Tech-Ref-Nr2, 2015). These curves have been developed in Europe to assess primarily community noise complaints. For different noise rating values there are sound pressure levels tabulated at different frequencies. This kind of “noise rating” is used to specify the maximum allowed sound power level at each frequency by selecting a single Noise Rating (*NR*) number. The Noise Rating (*NR*) is used across Europe, whereas in North America, the Noise Criterion (*NC*) levels are mostly used (Tech-Ref-Nr2, 2015). The Noise Criterion (*NC*) is similar to the Noise Rating (*NR*) but having a different set of values. The two rating methods have been developed for the same purpose, however these ratings do not reflect the subjective assessment of a sound pressure level transmitted through a partition. The Noise Rating (*NR*) and Noise Criterion (*NC)* rating (which measure acceptability) cannot be converted directly into an *A*-weighted sound pressure level value (which is supposed to measures loudness). Overall, the use of sound pressure levels to describe a sound or a noise is ambiguous because it is well known that two sounds having totally different spectra can have the same sound pressure level value.

A different way to show how modifications of the frequency characteristic of an airborne sound insulation may affect the resulting sound insulation was first investigated with electrical filters by Rademacher (1955). He investigated the subjective sound insulation by building up insulation curves with an electrical filter. Rademacher stated that: “*On the determination of an annoyance effect of the transmitted sound on the observer was refrained from the outset, as the term is too ambiguous and blurred as that common knowledge-statements can be made with him*.” This statement made in that early days is interesting because nowadays many researchers look especially to this “annoyance issue” when investigating noise problems.

Berglund et al. (1976) reported for example that annoyance is a linear function to loudness and therefore loudness can serve as the basis for predicting the annoyance of sound. This is, however not true in general which will be shown in this thesis.

And furthermore Scharf and Hellman (1978) suggested that the first step toward an accurate and valid measure of sound annoyance is the conversion of acoustic measures into a psychoacoustic measure such as loudness.

2.4.3 Calculation

When specifying the acoustic performance of a partition, it is common to describe the sound insulation by a single number. As was discussed in the foregoing section, the weighted sound reduction index, R_w, is a rating scheme given in EN ISO 717-1. The procedure of this rating scheme fits a reference curve to the measured sound reduction index curve. To calculate the airborne sound insulation, different approaches are available; however, in Europe, it is common to use the standard procedure described in EN 12354-1.

The calculation method of airborne sound insulation, according to EN 12354-1, requires many precise input data. In addition to the airborne sound insulation of the separating and all flanking elements of two neighbouring rooms, the type and rigidity of the connections of two adjacent components are most important. This characteristic physical unit is called the vibration reduction index K_{ij} (dB). The calculation of the resulting sound insulation index is an energetic summation of the sound transmittance along all flanking paths, which indicates that there is no global acquisition of sound transmittance. This allows for a realistic reflection of the real sound conductance. Finally, the geometric boundary conditions of the building are included in the calculation method of the standard EN 12354-1.

In general, the sound insulation of single-leaf, homogenous, massive constructions depends on the mass per area of the material. The mass per area is the product of the raw density of the material and its thickness. Some European countries developed special mass law equations that are specified in EN 12354-1, annex B.

Each of these equations is valid for all types of massive building materials but for different ranges of mass per area. The standard EN 12354-1 is discussed in more detail in the next chapter, so there is no further description on calculating airborne sound insulation in this section.

2.5 Summary

This chapter has shown that the problem in rating airborne sound insulation has a long history. The literature review showed that many attempts have been made to solve the problem. However, no satisfying conjunction is found in the literature relating objective measures of airborne sound insulation and its subjective assessment. The main research was observed to focus on objectives such as measuring and rating with single numerical figures. Many measurement and rating methods have emerged since the early investigations of airborne sound insulation between neighbouring housing, but no rating so far has considered using psychoacoustic parameters.

3 UNSUITABILITY OF CONVENTIONAL METHODS

According to the literature review, it is clear that the main research in rating airborne sound insulation was based on physical parameters such as mass and stiffness. No rating was considered in past and or current standards by means of psychoacoustic parameters in conjunction with physical measures. The assessment of airborne sound insulation in terms of a subjective measure requires a definition of its influencing parameters. The existing standards for measuring airborne sound insulation do relate in objective measures such as sound pressure (e.g. ISO 16283-1, 2014) or sound intensity (e.g. ISO 15186-2, 2003); even new measurement methods in building acoustics (ISO 18233, 2006) do not relate to subjective assessments. All measurement standards concerning building acoustics relate to the aforementioned objective measures.

Because hearing, or the awareness of intruding sound, is the measure of judgment to assess a sound insulation, the use of psychoacoustic measures, such as loudness and fluctuation strength, is needed. It is therefore required to understand the objective and subjective measures that define airborne sound insulation. In this chapter, the theoretical framework for this research is described that shows the unsuitability of conventional standards.

First, the standard theory of airborne sound insulation and relevant definitions used in this research are discussed. In section 3.1, the theory of sound transmission, the hearing-related measures used in this research, the threshold of hearing, loudness and loudness level, the frequency weighting to evaluate human responses to noise and the fluctuation strength, and the differentiation of the categories of noise, i.e., the types of sound signals are reviewed.

Second, a short experimental analysis is discussed comparing examples of airborne sound insulations that yield equally rated single values of sound reduction indices (Neubauer and Kang, 2015 b). This is presented in section 5.3.2.2.

3.1 Theoretical Analysis

The standard test method for the airborne sound insulation measurement uses two adjacent rooms with an connecting transmission path. The construction or panel tested is located between two rooms and a sound is generated in one of that rooms which is called the source room. The measurements of the sound pressure levels are taken in both rooms, i.e. the source and receiver room. The basic principle of this test method is therefore to obtain the sound level difference, which is then corrected for room characteristics, represented by the average reverberation time. The difference is obtained by the classical method using a random noise excitation.

As will be shown in the next section, the first theoretical formulation to determine the airborne sound insulation or transmission loss of a partition between two rooms was presented in the 1920s, followed by the first standardisations in the 1950s. The principle of this method to define the sound transmission loss or airborne sound insulation has not changed over the years, and the present test standards are in a physical sense equal.

The standards describe the measurement of objective measures such as the sound pressure level or sound intensity level. It is however, needed to quantify and measure this difference or loss when the reduction of sound vibration is discussed.

The most interesting objective questions are if all construction techniques or soundproofing materials work equally well and how much sound is being reduced. However, perhaps more importantly is the question, what frequencies of sound are being affected.

The sound reduction index is evaluated in 16 one-third octave bands of the frequency range from 100 Hz to 3,150 Hz. From these values the single-number presentation, or weighted sound reduction index, R_w, is determined according to ISO 717-1. To account for different sound spectra, the C and C_{tr} values are introduced. These are the values used to modify the measured sound insulation performance of a partition. The value is referred to as a spectrum adaptation value and is added to the weighted sound reduction index R_w.

The C or C_{tr} value for a building element varies according to the insulating material employed. In the Australian Buildings Codes Board (ABCB, 2004) an example is given: "*A 90 mm cavity brick masonry wall has a C_{tr} value of -6 dB, as does a wall constructed of 150 mm core-filled concrete blocks. By contrast, a brick veneer wall may have a C_{tr} of -12 dB. Smaller negative C, or C_{tr} values are more favourable than large negative values.*" As seen in the aforementioned section, the range of audible sound is from approximately 20 Hz to 20,000 Hz, and the range covered by speech sounds is from approximately 100 Hz up to 7,000 Hz. It is therefore questionable whether the transmitted sound below 100 Hz and above 3,150 Hz is omitted in the rating procedure. Even an expanded frequency range down to 50 Hz and up to 5,000 Hz does not fully cover the important frequency range of the audible range.

It is therefore most important to note that the human hearing system is frequency sensitive. This subject is discussed in more detail in section 3.1.2.

As demonstrated in section 4.2, simplifying the sound pressure level into an *A*-weighted sound pressure level does not resolve the problem of a subjective assessment.

From standards, it is known that the sound reduction index using the pressure method is

$$R = L_S - L_R + 10\ log\ (S/A)\ \text{dB} \tag{3-1}$$

where

L_S and L_R are the average sound pressure levels in the source and receiving room, respectively, S is the area of the test specimen in m² and A is the room absorption area of the receiving room in m².

It is seen that the sound reduction index is controlled by the sound level in the receiving room. The single-number value, or weighted sound reduction index, R_w, is then calculated according to ISO 717-1. If the sound reduction index is known, the averaged sound pressure level of the receiving room is

$$L_R = L_S - R + 10\ log\ (S/A)\ \text{dB} \tag{3-2}$$

Neglecting the logarithmic term or equate the terms S and A (e.g. $S = A = 10$ m²), yield in the frequency domain

$$L_{R(f)} = L_{S(f)} - R_{(f)}\ \text{dB} \qquad 50\ \text{Hz} \leq f \leq 5{,}000\ \text{Hz} \tag{3-3}$$

It is seen in Eq. (3-3) that the sound pressure level in the receiving room (L_R) is a function of the sound pressure level in the source room (L_S).

Here comes the requirement from theory on roles that the excitation has to be a random signal and the sound pressure in the source room has to be diffuse.

Therefore, pink noise, for example, is used as a test signal due to its characteristics of being a broadband excitation signal that contains an equal amount of noise power per octave, and the use of an omnidirectional loudspeaker to generate a diffuse random noise field in the source room is required.

Now, R_w, is the weighted sound reduction index in dB and is a laboratory-measured value, as defined in ISO 717-1. A higher number indicates a greater sound insulating power of the building element.

From psychoacoustic theory, it is known that an increase in the weighted sound reduction index R_w of a partition by 6 to 10 dB will decrease the perceived loudness in the receiving room by approximately half. How the sound insulating effectiveness of a partition depends on its R_w (or $R_w + C_{tr}$) values is detailed below. The value ($R_w + C_{tr}$) is R_w with the addition of a low frequency sound adaptation factor C_{tr}. (a negative number). From the frequency-dependent values, it is possible that two partitions can have the same R_w rating but different resistance to low frequency sound and thus a different $R_w + C_{tr}$. This approach enables the designer to select the optimum construction specification for the required application.

A further improvement is achieved by comparing the *R*-values of a construction against the noise spectrum for each noise. Because ISO 717-1 provides only two values, *C* and C_{tr}, the application is limited.

Remembering that R_w is the value measured in an acoustic laboratory, R'_w and D_{nTw} are measured on site.

$$D_{n,T} = L_S - L_R + 10 \log (T/T_0) \text{ dB} \qquad (3\text{-}4)$$

where *T* is the reverberation time in s in the receiving room and T_0 is the reference reverberation time in s, (T_0 = 0.5 s).

Hence, as Lang (2007) reported, in common living rooms, the reverberation time is approximately 0.5 s; therefore, the following relationship is assumed (i.e, in Eq. (3-2) S = A):

$$D_{n,T} = L_S - L_R = R \text{ dB} \tag{3-5}$$

Therefore, the conflict in assessing airborne sound insulation in terms of a subjective measure to have a more realistic value for a perception magnitude is not solved by the transformation of R into $D_{n,T}$, even with the spectrum adaptation terms C or C_{tr} applied.

The difference between the weighted sound reduction index R_w and the weighted apparent sound reduction index R'_w.is shown in Fig. 3-1 for clarification reasons.

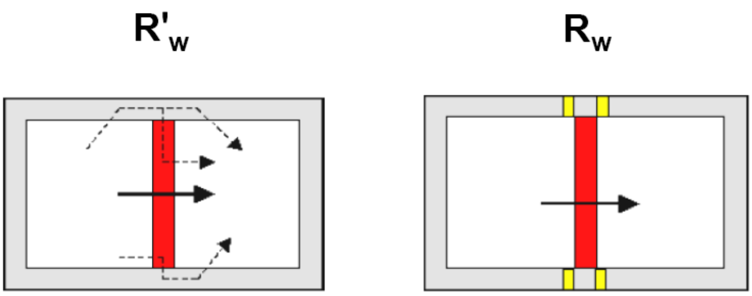


Figure 3-1: Weighted apparent sound reduction index R'_w (including flanking transmission) and weighted sound reduction index R_w (direct sound transmission without flanking transmission).

NB: D_{nTw} is the equivalent of R'_w, which are measured on-site.

3.1.1 Computational Determination of Sound Insulation of Building Components

To explore the differences between sounds that are filtered and unfiltered, the characteristics of the filter, i.e., the airborne sound insulation or transmission loss, the hearing-related parameters of loudness and the types of sounds have to be clarified.

3.1.1.1 Definition of Airborne Sound Insulation

With the purpose of computing airborne sound insulation, different calculation schemes were developed in the past. However, all approaches have similar foundations, i.e., the law of conservation of energy. As a result of this law, when the energy in a sound wave is incident on a surface, this energy must be absorbed, reflected or transmitted through the surface. Consequently, the sound insulation of a panel is merely a measure of how well it is able to prevent acoustical energy from going through it.

Airborne sound insulation is internationally specified in general by the sound reduction index *R* (sometimes referred to as transmission loss, *TL,* or sound transmission loss, *STL*). The definition of the direct sound transmission though a wall is illustrated in Fig. 3-2.

The sound power transmission coefficient τ is defined as the ratio of transmitted-to-incident sound power (Fahy and Gardonio, 2007).

Because values of the transmission coefficient are primarily small, the logarithmic index of sound transmission is used to quantity transmitted energy. It corresponds to ten times the decadal logarithm of the ratio between the impinging sound power W_i on an isolating component to the sound power W_t transmitted through it.

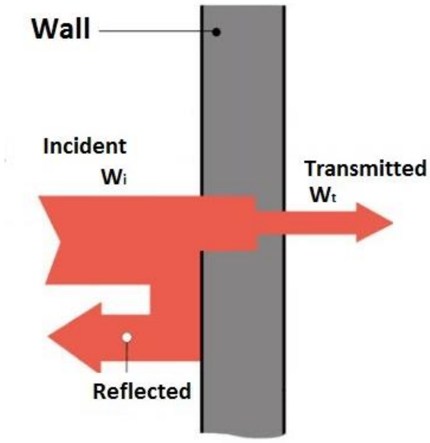


Figure 3-2: Definition of the direct sound reduction index *R*.

The formula to describe the sound reduction index *R* is given in Eq. (3-6):

$$R = 10\ log \frac{W_i}{W_t} = 10\ log \frac{1}{\tau}\ dB \tag{3-6}$$

where τ is the transmission coefficient.

As early as 1877, Lord Rayleigh (Lord Rayleigh, 1877) addressed the fundamental problem of the sound insulation of simple walls (London, 1949; Heckl, 1981). He developed a theory in which he considered the most important acoustic property of a component, i.e., the area-based mass *m'*.

Later on, early theoretical formulations to determine the sound transmission loss of a partition between two rooms were established in 1911 by Berger (Berger, 1911), and in the 1920s by Davis (Davis, 1925) and Buckingham (Buckingham, 1929) and in the 1930s by Schoch (Schoch, 1937) and finally in the 1940s by Cremer (Cremer, 1942).

London (1949) produced an elaborate and rigorous mathematical analysis of partition behaviour and developed a transmission formula based on Rayleigh's Random Incidence Mass Law modified by an acoustic resistance term (Weston and Green, 1969).

Heckl published in 1981 (Heckl, 1981), notes of a special lecture summarising how airborne sound insulation is related by various influencing factors. He illustrated that sound transmission through walls, ceilings, windows, and doors depends on mass-per-unit area, as Lord Rayleigh investigated, and on bending stiffness, which was verified by Berger.

In the early forties, Cremer (Cremer, 1942) first showed that sound transmission loss depends upon the angle of sound incidence and described this context as the coincidence effect. Further research in the following years led to the findings from various researchers that the sound insulation also depends on, e.g., the damping and stiffness of interlayers and sound bridges (in cases of double walls), the size and shape of partitions, mounting conditions, the influence of flanking walls, and unwanted effects such as slits (Heckl, 1981).

Many of the results obtained in buildings can be explained at least qualitatively. Although sound transmission has been investigated for a long time, there remain open questions, particularly with respect to inhomogeneous walls and multiple walls of finite size (Heckl, 1981). Examining the up-to-date literature on airborne sound insulation, there is ongoing research due to unsolved problems.

In general, as illustrated in the foregoing section, a wall or partition has different effects on the sound insulation according to the properties of stiffness, damping and mass.

Watters (1959) first suggested that the transmission behaviour of a panel can be divided into three regions: "*1. At low frequency there is an upward slope of 6 dB per octave, where something like mass law behaviour exists, 2. in the higher frequencies a steeply rising curve* *sloping at approximately 10 dB per octave is observed, and 3. a middle region of great irregularity which is best by coincidence dips.*" (Weston and Green, 1969).

A sketch of the transmission behaviour of a single panel is shown in Fig. 3-3, in which the aforementioned regions of the various characteristic frequency ranges are indicated. The three cases of interest are defined in more detail as:

(I) The resonance region, i.e. below the natural frequency (f_0), the airborne sound insulation, is controlled by the sound transmission coefficient of the material.

(II) Above the first natural frequency, the airborne sound insulation is determined merely by mass per unit area, and is largely independent of damping and stiffness (Fahy, 1987); it increases with frequency at 6 dB per octave and 6 dB per doubling of mass.

(III) At the critical frequency (f_c), a deep reduction in the sound insulation curve occur above that frequency; the sound insulation increases by a rate of about 9 dB per octave.

For each of these cases, a specific equation exists to describe the airborne sound insulation.

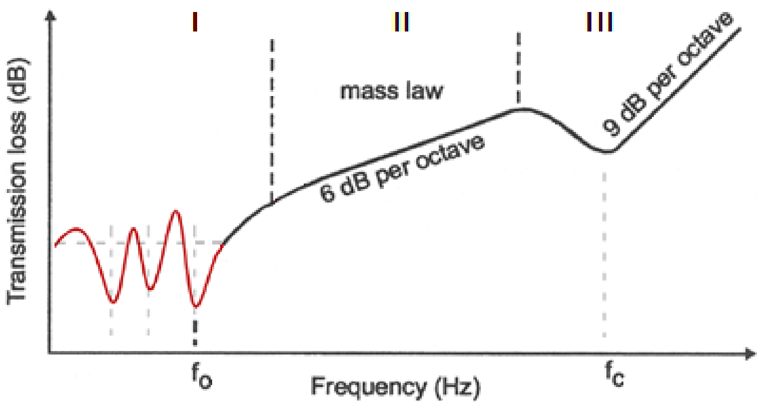


Figure 3-3: Typical form of the transmission loss of a single panel as a function of frequency.

This typical transmission behaviour of a single panel, as shown in Fig. 3-3, can be described mathematically with equations 3-7.1 – 3-7.3 for each of the cases described above.

I: $$R = 20\log\left(\frac{s}{f}\right) - 20\log\left(4\pi\,\rho_0 c_0\right)\ \text{dB} \tag{3-7.1}$$

II: $$R = 20\log\left(m' f\right) - 20\log\left(\frac{\rho_0 c_0}{\pi}\right)\ \text{dB} \tag{3-7.2}$$

III: $$R = 20\log\left(m' f\right) - 20\log\left(\frac{\rho_0 c_0}{\pi}\right) + 10\log\left(\frac{f}{f_C} - 1\right) + 10\log\eta - 2\ \text{dB} \tag{3-7.3}$$

where *s* is the stiffness of the partition, *f* frequency, *d* sound insulation, ρ_0 density of the air, c_0 is the speed of sound in air, *m'* mass per unit area of the partition, η is the loss factor, f_c is the critical frequency, and f_0 is the natural frequency of the partition.

The natural frequency (f_0) is, in general, of only minor importance in practice because it occurs at very low frequencies due to the usual indoor dimensions of a building (Furrer and Lauber, 1972). Tadeu and Mateus (2001) explained in detail that: "*The natural frequency, i.e., the natural vibration modes of the panel, are related to its transversal movement in pure flexion, generally at low frequencies, and to the movement of bending waves along the panel, usually occurring at higher frequencies. These dips in insulation primarily occur at eigenfrequencies related to the panels' flexion-induced transversal movement.*" The resonant frequencies or natural modes depend on the boundary conditions describing the mounting, thickness, and dimension of the plate (Leissa, 1969). The boundary conditions on the four edges of a wall are usually not readily apparent or specifically determined by the construction.

The calculation of the natural frequency (f_0) is not further considered and is referred to the literature (Sewell, 1970; Quirt, 1982; Ljunggren, 1991; Bies , Hansen, 2003).

In the early 1940s, Cremer (1942) solved the problem of the coincidence effect. He described this "coincidence effect" as a kind of resonance occurring when the bending wavelength in the panel and the sound wavelength in air became equal. This "coincidence effect" always occurs at a certain frequency when a sound wave in air strikes for example a wall at a certain angle of incidence so that the two wave speeds became equal yield a kind of resonance. The theory postulates for that event a critical frequency, or lowest coincidence frequency. At this frequency a relatively low sound insulation occurs, and this frequency f_c is calculated by equation (3-8):

$$f_C = \frac{c^2}{1.8t\, c_L} \text{ Hz} \tag{3-8}$$

where c is the sound velocity of air, t is the thickness of the panel, c_L is the longitudinal speed of sound along the panel.

The longitudinal wave speed is determined by the properties of bulk modulus B and the density ρ of the structure. When two dimensions of the structure are small with respect to wavelength, the wave speed is dictated by Young's modulus E instead of the B and is written as specified in equation (3-9):

$$c_L = \sqrt{\frac{E}{\rho}} \text{ ms}^{-1} \tag{3-9}$$

where E is the Young's modulus of the panel, ρ is the density of the panel.

This resonance dip in region III in Fig. 3-3 caused by the coincidence effect typically occurs around an octave below the lowest coincidence frequency (f_c). The depth of this dip depends on the damping of the panel, i.e. of the wall or in general the damping of the material.

Below that frequency range of coincidence, i.e., region II in Fig. 3-3, the transmission loss or airborne sound insulation, is determined by the mass law, which refers to Eq. (3-7.2).

Above the coincidence zone, the transmission loss depends on the frequency, which is given by Eq. (3-7.3). And the damping controls the amount of the resonance dip. Equation (3-7.3) indicates that above the critical frequency the airborne sound insulation increases about 9 dB per octave, as long as the loss factor is constant (Tadeu and Mateus, 2001).

It is therefore highly important that the critical frequency of a material is either above or below the frequency range that is relevant for noise reduction based on standard regulations, e.g., from ISO 717-1.

The above equations are examples of how a sound transmission loss for a single leaf of a homogeneous panel in a diffused sound field can be calculated. Other models also exist for double panels, double walls with studs, rooms or any wall system with various air gaps with or without absorbers inside.

In general, if measurements are made, deviations are observed compared with the computed values. This insufficient compliance of calculation and measurement is due to several reasons, e.g. unspecified boundary conditions, non-diffuse sound field in the rooms, imperfect omnidirectional sound source, improper model use, etc., which are discussed in detail in the literature (Beranek et al., 1992; Cremer et al., 1996; Gösele, 1990; Heckl et al., 1985; Lepping-ton, 1996; Ljunggren, 1991; Maidanik, 1962; Osipov et al., 1997; Rindel, 1994; Timmel, 1991; Warnock et al., 1993).

Alternately, the accuracy of prediction methods for sound transmission loss was investigated by Ballagh (2004). He stated: "*that sound insulation of typical building constructions using either masonry or lightweight cavity construction can be predicted with acceptable engineering* *accuracy over the frequency range 50 Hz - 5,000 Hz using simple and readily available expressions*.” In order to quantify the accuracy Ballagh (2004) made comparisons between results obtained through theory and measurements. From the published measurements of the National Research Council (NRC) in Canada (Halliwell, 1998; Warnock, 2000) Ballagh made predictions for the constructions and found that the mean difference in sound transmission loss between laboratory measurement and calculated results was less than 0.5 dB. He summarized that 90% of the results were found to lie within ± 2.5 dB.

Figure 3-4 shows the difference of measured transmission loss less predicted, i.e. the difference between theory and measurement, as a function of frequency.

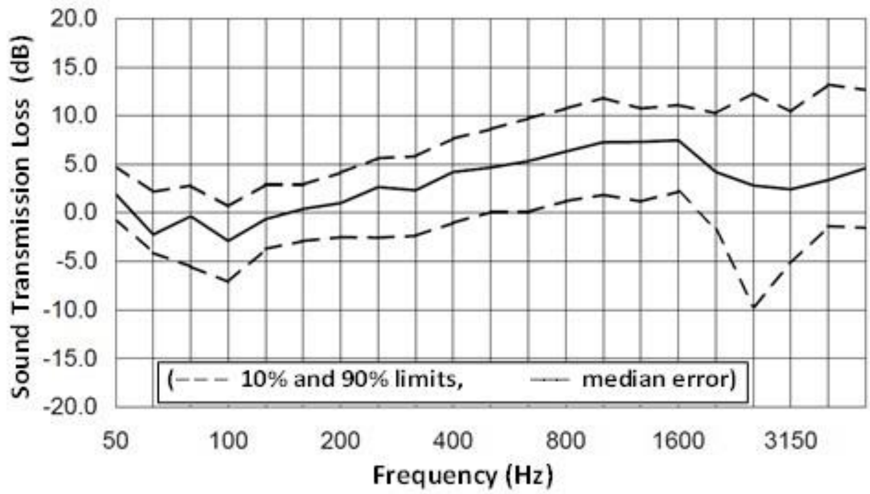


Figure 3-4: Measured less predicted for 112 walls (Halliwell, 1998), (Ballagh, 2004).

It is observed in Fig. 3-4 that the differences are smallest at low frequency. It is further seen that the prediction models tends to underestimate by approximately 5 dB at midrange frequencies. This is in line with results published by Praščević et al. (2012). Wittstock (2007) carried out an analysis of the factors that contribute to the global uncertainty of measured airborne sound reduction and its weighted single numbers. He compiled an overview of round robin tests (Wittstock, 2005), where different types of element were circulated for measurements in European laboratories. Such round robin tests have been conducted for different materials, such as lime brick walls, lightweight walls, and windows (Pompoli, 1994; Schmitz et al., 1999; Meier, et al., 1999).Figure 3-5 illustrates the scatter of results obtained. As shown by this figure, the scatter of results reported from these round robin laboratory tests was unexpectedly large. It is seen by comparison that a large deviation is observed in the frequency range below 100 Hz and that the difference between the highest and lowest results at 50 Hz is more than 25 dB.

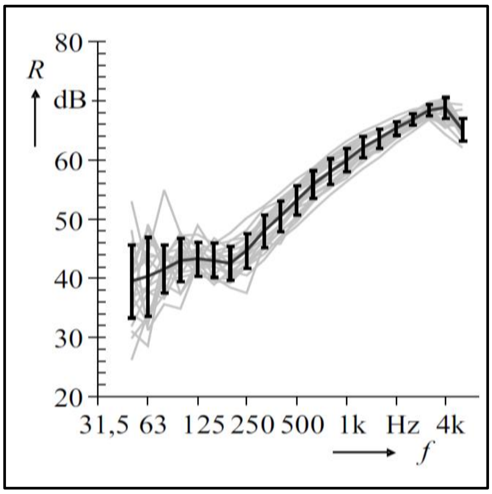


Figure 3-5: Sound reduction index of sand-lime brick walls. The black line indicates the average and standard deviation. The grey line indicates the individual measurement results from 20 different laboratories (Wittstock, 2007).

The complexity of sound insulation and the uncertainty of the prediction, as well as measurement is evident from the previous detailed explanations.

3.1.1.2 European Standard for Calculating Sound Insulation

The European standardization organization has collected models to predict airborne apparent sound insulation between adjacent rooms in the field based on the performance of the involved building elements. These models take into account flanking transmission through structural connections between elements of adjacent rooms.

In Europe, the calculation of airborne sound insulation is regulated in the European standard EN 12354-1 (EN 12354, 2000) internationally, the standard used is ISO 15712-1 (ISO 15712, 2005) which is actually identical to the European standard EN 12354. According to the respective codes of EN 12354 (ISO 15712), a planner is able to design and verify the acoustic isolation of buildings. The codes of EN 12354 are recognized world-wide and referenced in most of the international state codes developed in recent years; during the project phase, they permit the prediction of the building spaces' acoustic comfort, starting from the acoustic characteristics of the constructive elements to be used, which is useful in the optimum design of the building. The standard EN 12354-1 consists of two models describing the weighted apparent sound reduction index. One, described as the detailed model, is basically a frequency-dependent calculation procedure. The other model is called the simplified model. The simplified calculation model predicts the weighted apparent sound reduction index on the basis of the weighted sound reduction indices of the respective elements (Szudrowicz and Izewska, 1995). It considers the weighting in accordance with EN ISO 717-1. The model is given for the weighted sound reduction index, R_w, but can also be applied to the single number rating with the spectrum adaptation term, i.e., $R_w + C$. The resulting estimate of the building performance is given in the same type of single number rating as is used for the building elements, i.e., R'_w or ($R'_w + C$).

The simplified model restricts the application to direct and flanking transmission. It takes into account the structural damping but only in terms of an average, neglecting the specifics of the situation. That means, that each flanking element is essentially considered to be the same on the emission and receiving side (Szudrowicz and Izewska, 1995). If the values for the vibration reduction index depend on frequency, the value at 500 Hz may be taken as a good approximation, but the result can then be less accurate (EN 12354, 2000).

The standard EN 12354 consists of several parts that cover the most important acoustic properties of buildings; airborne sound transmission between rooms is covered in part 1.

The calculation methods are described by each of the EN 12354 standards. The calculation procedure is illustrated when the individual transfer paths of sound are considered within a building.

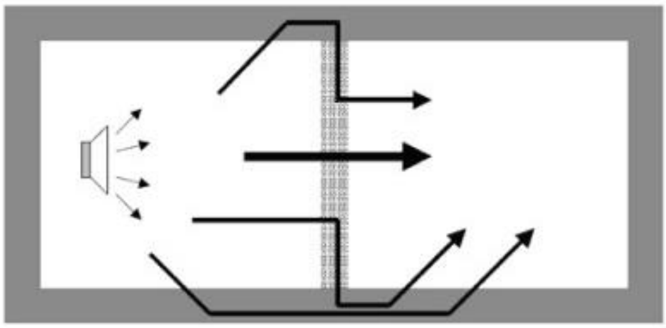


Figure 3-6: Transfer paths of sound energy between two rooms.

In addition to the direct transmission, as shown in Fig. 3-2, flanking transmission occurs via different paths, as indicated in Fig. 3-6.

The calculation procedure according to EN 12354 aims to determine the individual transfer paths to calculate the total sound insulation.

The input and output data of this procedure can be combined in essence with the measurement procedures according to ISO 16283, which is an important advantage because these values are very common and often known for a wide variety of components.

Moreover, a simplified model within the forecasting methods, based on the weighted deposit information, can be used on a detailed model.

The main difference with the simplified model is that results are calculated in a frequency-dependent manner in octave bands from 125 Hz to 2,000 Hz, or in third octave bands from 100 Hz up to 3,150 Hz.

After a detailed calculation, the result can be calculated with the usual procedures as provided by ISO 717 to build a single number descriptor.

Using the prediction model of EN 12354-1, the designer is supposed to make certain assumptions when the model of EN 12354-1 is specified, which is, in general, a “shoe-box model,” to approximate the real layout of the rooms in a building.

These assumptions influences the calculation result and should therefore be based on both theoretical understanding and practical experience of building constructions.

One of the most important assumption is the choice of the junctions between building elements which is needed as input to the EN 12354-1 calculation model. Input data for the elements (walls, slabs, flooring, windows, etc.) may be obtained by several methods. The most common are measurements in the laboratory and in buildings, as well as theoretical calculations or considerations on the basis of experience.

The accuracy of the models defined in the standard EN 12354-1 is described as follows: “*The calculation models predict the measured performance of buildings, assuming good workmanship and high measurement accuracy. The accuracy of the prediction by the models pre-*

sented in EN 12354-1 depends on many factors: the accuracy of the input data, the fitting of the situation to the model, the type of elements and junctions involved the geometry of the situation and the workmanship. It is therefore not possible to specify the accuracy of the predictions in general for all types of situations and applications. Data on the accuracy will have to be gathered in future by comparing the results of the model with a variety of field situations. However, some indications can be given. The main experience in the application of similar models has been so far with buildings where the basic structural elements are homogeneous, i.e. brick walls, concrete, gypsum blocks etc. In those situations the prediction of the single number rating by the detailed model is on average correct (no bias error) with a standard deviation of 1.5 dB to 2.5 dB (the lower value if all aspects are taken into account, the larger to complex situations and when neglecting the structural reverberation time). Predictions with the simplified model show a standard deviation of about 2 dB, with a tendency to over-estimate the insulation slightly. In applying the predictions it is advisable to vary the input data, especially in complicated situations and with atypical elements with questionable input data. The resulting variation in the results gives an impression of the expected accuracy for these situations, assuming similar workmanship." (EN 12354, 2000).

In the literature, it is stated that the simplified model estimates the weighted apparent sound reduction index in a more secure way (Andrade, et al, 2005) and as Esteban et al. (2005) have shown, the simplified model tends to overestimate slightly the sound insulation, whereas the detailed method underestimates it. A good agreement between measured and predicted apparent weighted sound reduction index for the simplified model was also reported by Ruff and Fischer (2009). The simplified model is described in Appendix III.

3.1.2 Threshold of Hearing

Hansen (2010) states: "*The threshold of hearing is defined as the level of a sound at which, under specified conditions, a person gives 50% correct detection responses on repeated trials*".

The threshold of hearing varies with the frequency of the sound (Fig. 3-7) and may vary for different people and at different times for the same person, depending on age, physiological condition, and training. The reference threshold value is specified in ISO 226 (ISO 226, 2003).

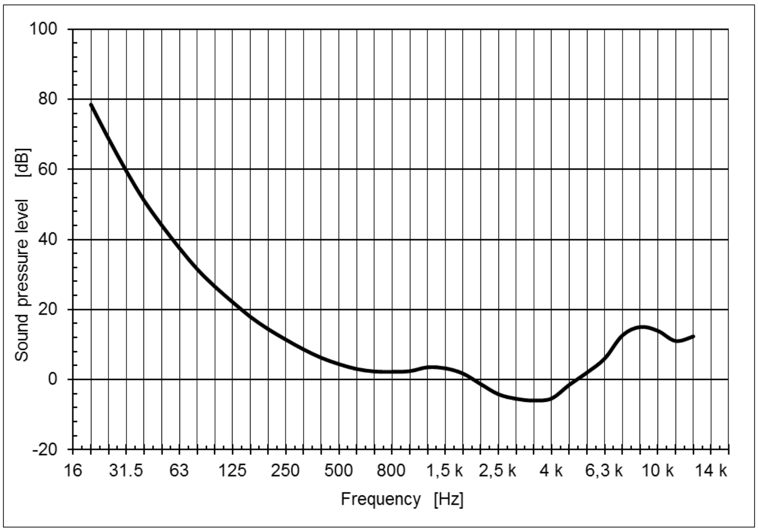


Figure 3-7: The hearing threshold according to ISO 226.

From Fig. 3-7, it is seen that human hearing is most sensitive at approximately 3k Hz. Above and below this frequency, the sensitivity decreases. Above 10k Hz, the sensitivity of the ear rapidly decreases.

It is noted that the threshold in quiet corresponds to 3 dB at 1k Hz and not to 0 dB; this equal-loudness contour is indicated by 3 phons (Zwicker and Fastl, 1999).

3.1.3 Loudness and Loudness Level

At the threshold of hearing as depicted in Fig. 3-7, a sound is just loud enough to be heard, or in other word to be detected by the human ear. Hansen (2010) pointed out: "*Above that threshold, the degree of loudness is a subjective interpretation of the sound pressure level or intensity of the sound*." The sensation that corresponds most closely to the sound intensity of the stimulus is loudness (Zwicker and Fastl, 1999). A model and a procedure for calculating the loudness of steady-state sounds were published as early as 1958 and 1960 by Zwicker (Zwicker, 1958, 1960) and later by Moore and Glasberg (Moore and Glasberg, 1997).

The procedure introduced by Zwicker is based on the specific loudness and was adopted by ISO R 532B in 1966, and it has been used until now (ISO 532, 1975). The calculation of specific loudness was also standardized by the German standard DIN 45631 (DIN 45631, 2010). A procedure for calculating the loudness of temporally variable sounds was published in 1977 by Zwicker (Zwicker, 1977) and in 2002 by Glasberg and Moore (Glasberg and Moore, 2002). While ISO 532B treats stationary sounds, DIN 45631 also describes the calculation of time-dependent loudness, estimating the temporal effects of loudness by means of filters. It is noted that the DIN calculation method is identical to the Filter/ISO 532B method, except that DIN automatically uses 6^{th}-order filters. The perception of loudness is related to the sound pressure level (SPL) and is defined as a level of 40 dB of a 1k Hz tone referenced for loudness sensation, i.e., 1 sone. In other words, a sone is equivalent to 40 phons, which is defined as the loudness level (L_N) of a 1k Hz tone at a 40-dB sound pressure level. The units used to measure loudness are:

- Sone (loudness *N*)
- Phon (loudness level *L*)

The relationship between loudness level and loudness is shown in Fig. 3-8.

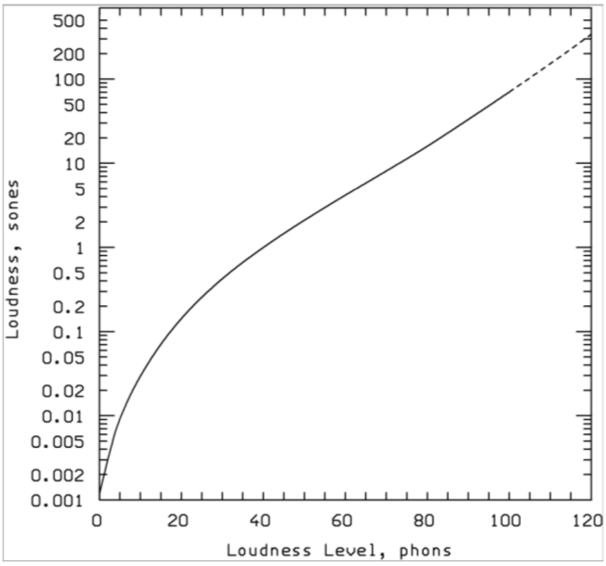


Figure 3-8: Loudness in sones as a function of the loudness level in phons (ANSI, 2007).

For the evaluation of exposure to noise the model of loudness is very important. It have been made many attempts in the past to determine equal loudness level contours. The earliest measurements of equal loudness level contours were reported by Kingsbury (1927).

Suzuki and Takeshima (2004) state: "*The loudness of a sound strongly depends on both the sound intensity and the frequency spectrum of a stimulus. For sounds such as a pure tone or a narrow-band noise, an equal-loudness-level contour can be defined. This contour represents the sound pressure levels of a sound that give rise to a sensation of equal-loudness magnitude as a function of sound frequency. The equal-loudness-level contours are so foundational that they are considered to reveal the frequency characteristics of the human auditory system.*"

To introduce the sone as the unit of loudness many efforts have been made. These attempts have been designed to yield scale numbers roughly related to the loudness. However, these scale numbers have not been used in practice for noise evaluation and control.

Instead of that, “equal-loudness contours” have been established to rate the loudness of sounds. These contours have been determined through psychoacoustical experiments and implicate therefore subjective responses.

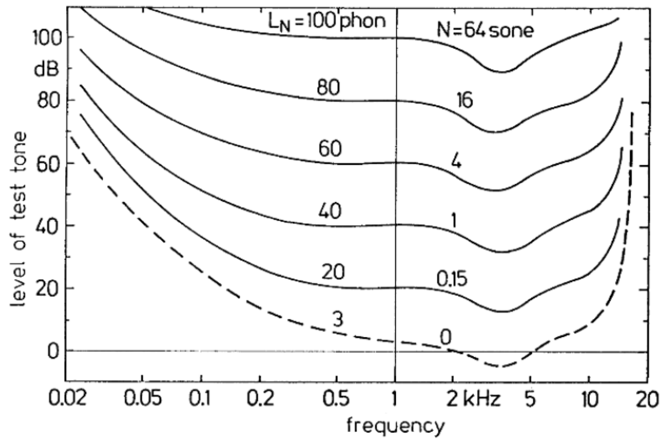


Figure 3-9: Equal-loudness contours for pure tones in a free sound field (Zwicker and Fastl, 1999).

The parameter in Fig. 3-9 is expressed in loudness level, L_N, and loudness, N. Each line represents an equally loud perceived sound pressure level at a certain frequency. The dashed line indicates the hearing threshold. This is in a noiseless environment the lowest level of a pure tone that the average human ear with normal hearing can hear. Below this curve, no sound can be heard at all (ref. hearing threshold). The equal-loudness contours are standardized in ISO 226 (ISO 226, 2003) and depicted for reference in Appendix IV. It should be noted at this point that Zeller and Elsner (V56-2, 1952) already stated in 1952 that: “*Less than 3 phon loudness level reductions are worthless, if the volume is not just reduced below the noise level. Reductions of 3 … 5 phon are noticeable and justify a modest investment. A reduction of 10 phon, i.e. half as strong according to sensation, is a success.*”

3.1.4 Frequency Weighting

The human ear is frequency sensitive, as was discussed in the previous sections. To quantify human exposure to noise in an adequate manner the applied measuring system need to account for this difference in sensitivities over the entire audible range. For this objective, some "filters" in the measuring system have been developed in the past. These frequency weighting networks or filters "weight" the frequency contributions to the total sound level. The sound pressure levels as a function of frequency will be lowered or amplified before being combined together to yield a total level (Hansen, 2010). Frequency weighting has a long history, and, as early as 1952, Zeller and Elsner (V 56-2, 1952) stated that: "*The subjective loudness measurement is already long superseded by objective measurement techniques.*" They presented in their publication the frequency weightings together with the Fletcher-Munson curves. This figure is depicted below in Fig. 3-10 as a copy of their original work.

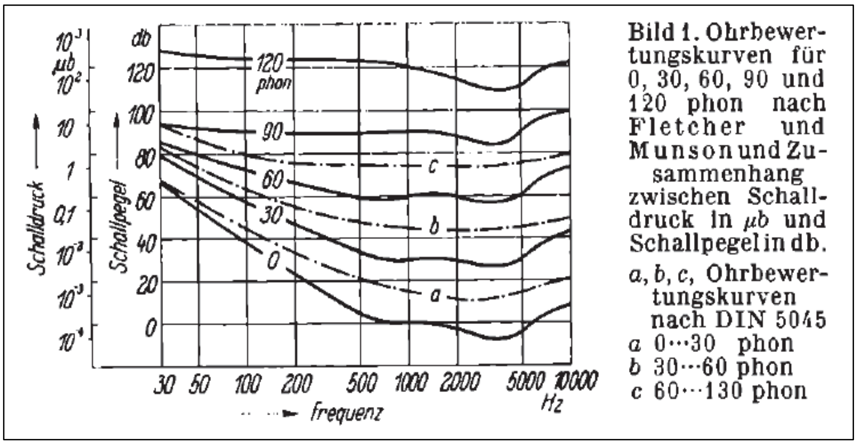


Figure 3-10: Original text: "*Ear rating curves for 0, 30, 60, 90 and 120 phon according to Fletcher and Munson and relationship between sound pressure in μb and sound pressure level in dB. a, b, c, ear rating curve according to DIN 5045. a: 0-30 phon, b: 30-60 phon, c: 60 · 130 phon*", (V 56-2, 1952).

In the very early beginning, it was generally difficult to measure loudness level. The construction of loudness level meters has dispensed with extensive reconstruction of ear rating curves. It was therefore internationally agreed that, for ranges of 0-30 phons, 30-60 phons and 60-130 phons, only one rating curve has to be applied in sound level meters, as depicted in Fig. 3-10. It was at that time, however, already observed that the simplified rating curves for loudness measurements involve a disadvantage. Because the curves cluster in equal volume at low frequencies, a sound level change of 5 dB corresponds to a change of approximately 10 phons at, e.g., 100 Hz (V 56-2, 1952). A lot has changed since then, and, currently, the most applied weighting in noise control is the *A*-weighting curve, which is internationally standardised. Its characteristics are specified in IEC 61672-1 (IEC 61672, 2013). The *A*-weighting curve is shown in Fig. 3-11.

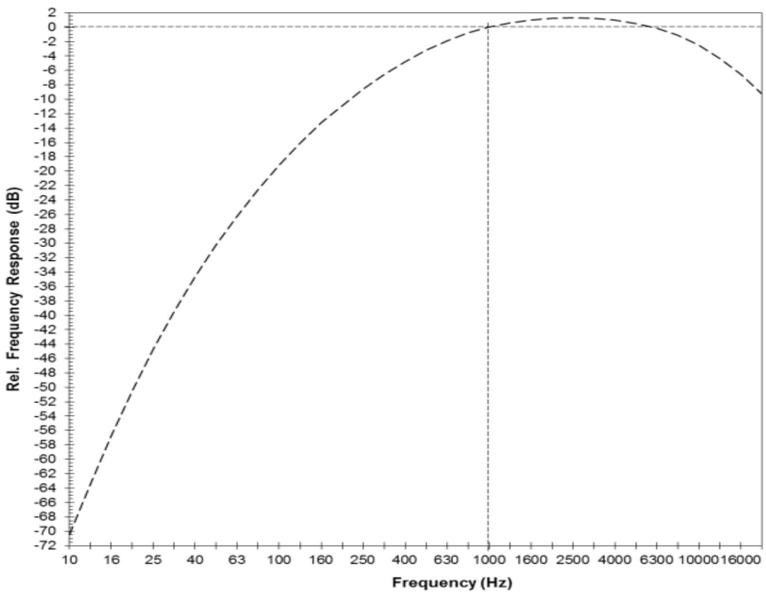


Figure 3-11: Frequency response of the *A*-weighting Filter (IEC 61672, 2013).

The "*A*" network follows the frequency response of the equal loudness contour of around 40 phons. (Hansen, 2010). There exist other weightings, such as "*B*," "C," and "*D*" networks, but, except for *C*-weighting, they are no longer used in noise evaluations. It should be mentioned that there also exists a “*Z*” weighting. *Z* stands for “Zero” frequency weighting, which implies no frequency weighting. In combination with masking curves to calculate which spectral components are inaudible, any part of an audio spectrum having amplitude (level or strength) below the threshold of hearing may be ignored without any audible change to the signal. In practice, filters such as *A*-weighting attempt to adjust sound measurements to correspond to loudness as perceived by the average human. Some researchers, however, have noted that the *A*-weighting sound pressure level does not take into account the spectral content of the sound and hence, ignoring the spectrum it can grossly misrepresent the perceived loudness (Fastl, 1985; Zwicker, 1985; Hellmann, 1987; Kuwano, 1989; Berglund, 1995; Shomer,2001; Quinlan, 1994; Aarts, 1992).

Lawrence (1969) states as early as 1969: “*That the decibel A-scale is measured with a sound level meter incorporating a weighting network which matches the response of the ear to different frequencies. A single number that rates sound with regard to their subjective loudness is obtained, but no information is available with regard to spectral composition.*”

Finally, Hellman and Zwicker (1987) concluded in their study that, “when two sounds with different spectral shapes are combined, the *A*-weighted sound pressure level is unable to predict either the loudness or the annoyance of the sounds.”

Additionally, as Bauer and Vian (1981) have shown: “*The A-weighted ratings of the transmission loss provided by the insulation curves poorly predicted the subjective assessments. Likewise, the ISO and ASTM recommended sound transmission loss rating methods also poorly predicted the annoyance reactions.*” Thus, it is summarized that *A*-weighting might not be the first choice as a reliable measure of subjective loudness.

3.1.5 Fluctuation Strength

The psychoacoustic magnitude fluctuation strength describes temporal variations of sounds and is often used for the subjective judgment of sound impression. Fluctuation strength is elicited by slower sound variations up to approximately 20 Hz and reaches a maximum for modulation frequencies approximately 4 Hz (Fastl, 2006). Fluctuation strength is an important measure in the assessment of human speech. Zwicker and Fastl (1999) state: "*The maximum fluctuation strength for a modulation frequency of about 4 Hz finds its counterpart in the variation of the temporal envelope of fluent speech: at normal speaking rate, 4 syllables/second are usually produced, leading to a variation of the temporal envelope at a frequency of 4 Hz. This may be seen as a dedication of the excellent correlation between speech and hearing system.*"

The calculation of the fluctuation strength in this research was performed using ArtemiS V11 software (Advanced Research Technology for Measurement and Investigation of Sound and Vibration) of the company HEAD acoustics GmbH.

For fluctuation strength, ArtemiS calculates the partial fluctuation strength from the modulation depths of partial signal bands and adds them together to determine the total fluctuation strength. The calculation method of the fluctuation strength is similar to the algorithm for the calculation of the roughness in the way that the maximum of the fluctuation strength is obtained at 4 Hz instead of 70 Hz (Head-acoustics, 2014). As was shown in (Neubauer and Kang, 2011 a) the calculated specific roughness yields zero for sound insulation values of 50 dB and 60 dB. Therefore, roughness is not believed to be an appropriate measure because of the fact it yields zero for the high sound insulation value using white noise. This agrees with findings in (Aures, 1985; Daniel et al., 1997), which show that the examined unmodulated white noise has no or only negligible roughness. Furthermore, Daniel and Weber (1997) demonstrated that, for small frequency bandwidths, the random envelope fluctuation is approximately 6 Hz, yielding a calculated roughness of approximately 0 asper. For that, Zwicker and Fastl (1999) stated that subjects will have difficulties in differentiating between roughness and fluctuation strength. This means that, in the overlapping area of smaller modulation depth, fluctuation strength is a prime measure. Therefore, it is assumed that fluctuation strength is of appropriate magnitude to describe the signal in terms of psychoacoustic quantity.

The fluctuation strength has the unit “vacil” which has its origin in the Latin word “vacillare” that means in English like “fluctuate, shake or tremble”. One vacil is defined as the fluctuation strength of a 1,000 Hz tone at 60 dB that is 100% amplitude modulated at 4 Hz. At that 4 Hz modulation frequency maximal values are found to occur (Zwicker and Fastl, 1999).

The following relation given by Zwicker and Fastl (1999) shows the variation of fluctuation strength (*Fls*) with masking depth (ΔL) and modulation frequency (f_{mod}):

$$Fls = \frac{0.008 \cdot \int_0^{24Bark} \Delta L \cdot dz}{\left(\frac{f_{mod}}{4Hz}\right) + \left(\frac{4Hz}{f_{mod}}\right)} \qquad (3\text{-}10)$$

The fluctuation strength metric has not yet been standardised. Several proposed methods of calculation exists.

3.1.6 Types of Noise

Depending on the temporal variations in sound pressure level noise can be categorized as steady, non-steady or impulsive (ISO 12001, 1996). By "noise" it is meant that the spectrum of the sound is complex, i.e., does not consist of only a single tone or even several pure tones. In this research, a steady and a non-steady sound type are used.

Steady noise is a sound with very small or almost no fluctuations of sound pressure level. This type of noise is also known as broadband noise, such as pink noise or white noise (Hansen, 2010).

N**on-steady noise** is a sound with significant fluctuations of sound pressure level. Hansen (2010) differentiated this type of noise into intermittent noise and *fluctuating noise*.

Fluctuating noise is a sound for which the level changes continuously and can also contain *tonal noise* (Hansen, 2010).

Tonal noise is a sound which is either continuous or fluctuating and is characterised by a single frequencies. This type of noise is supposed to be more annoying than broadband noise (Hansen, 2010).

3.2 Experimental Analysis

From basic statistics it is known that a measured value only approximates the true value. To obtain the sound reduction index described in Eq. (3-1) assumes strict requirements for laboratories and test arrangements for its successful application (Hongisto, 2000).

The measured value might therefore severe affected by the measurement environment and measurement arrangements. In the literature (ISO 140, 1991; ISO 12999, 2014), the uncertainty of sound insulation in building acoustics is specified. As Hongisto (2000) states: "*The reproducibility values, which apply between different laboratories, are expected to lie within 2.5 and 9.0 dB, depending on the frequency. The repeatability values, which apply in a single laboratory, are expected to lie within 1.5 and 4.5 dB. Both values are largest at low frequencies*".

Furthermore, in the literature (Fausti, et al., 1999), results were reported for an extensive round robin test where a total of 24 laboratories took part, 21 belonging to the European Community, justifying significant statistical conclusions. Two test structures were constructed, a double lightweight wall and a single lightweight wall. Both test structures were built of plasterboard. The airborne sound insulation were measured. The main result of the round robin test was the significant difference obtained for the reproducibility for the double lightweight wall with values up to 12 dB at middle-high frequencies.

These are impressive results, which show that the sound pressure level is not reliable for describing the subjectively perceived size of hearing impression. It is remembered that a subjective term for the sensation of the magnitude of sound is loudness and, as known from psychoacoustics, a 10-dB increase in sound pressure level is perceived as a doubling of subjective loudness, whereas, at low frequencies (20 Hz to 200 Hz), an increase of as little as 5-6 dB is perceived as a two-fold increase in the subjective loudness (Zwicker, 1958; Zwicker and Scharf, 1965).

In general, to perceive a sound pressure change, the threshold area must vary by approximately 3 dB. At higher sound pressure levels, from approximately 60 dB, differences are already perceived with an increase of 2 dB. That is, doubling the acoustic energy (3 dB) is just the border of distinction, i.e., it is just detectable, while a doubling of the subjectively perceived volume requires a change of 10 dB. That is an indication that it is difficult to find a single numerical value that corresponds to a subjective related measure to describe an airborne sound insulation value. This will be demonstrated in an example by conducting an airborne sound insulation measurement and calculating different rating values, which yield different results. This is shown in Tab. 3-1, where the measured sound pressure levels (L_S, L_R), background noise level (L_{BGN}) and reverberation time (T) are shown. The frequency-dependent calculations are performed according to ISO 717-1. Computed are the frequency-dependent apparent sound reduction index R', the level difference D, the normalized level difference D_n, and the standardized level difference D_{nT}.

It is noted that the standardized level difference D_{nT} is similar to the normalized level difference D_n, but it adjusts the measured difference to a standardized reverberation time of T = 0.5 s. This reverberation time value of 0.5 s is often cited as a roughly average for a medium-sized carpeted and furnished living room. The standardized level difference does not require detailed knowledge of the dimensions of the test rooms. The single numerical value of the aforementioned frequency-dependent ratings is derived according to the procedure of ISO 717-1.

From the computed sound reduction index R', the weighted apparent sound reduction index R'_w is obtained and, from the level difference D, the normalized level difference D_n, and the standardized level difference D_{nT}, as well as the respective weighted rating values, are obtained in the same manner. It is noted that the D_w value will be identical to $D_{nT,w}$ when T = 0.5 seconds. The computed single rating values and the respective spectrum adaptation terms C, and C_{tr} are depicted in Tab. 3-2.

Table 3-1: Measured airborne sound insulation of a stud partition with gypsum fibre boards (t = 150 mm) in an empty room of volume 107.7 m³ and a partition area of 24.8 m² yielding different rating values.

F	**Source L_S**	**Receiving Room L_R**	**Background Noise L_{BGN}**	***T_{60}***	***A***	**Rating values in dB**			
(Hz)	(dB)	(dB)	(dB)	(s)	(m²)	***R'***	***D***	***D_n***	***D_{nT}***
50	82.2	73.0	31.7	5.1	3.4	17.8	9.2	13.9	19.3
63	80.6	66.6	34.4	3.8	4.5	21.4	14.0	17.5	22.9
80	86.1	64.6	36.6	4.1	4.2	29.2	21.5	25.2	30.6
100	90.5	68.0	34.7	5.4	3.2	31.4	22.5	27.4	32.9
125	95.2	69.1	32.7	4.4	3.9	34.1	26.1	30.2	35.6
160	99.8	69.5	32.7	4.3	4.0	38.2	30.3	34.3	39.7
200	98.9	64.9	25.3	3.7	4.6	41.3	34.0	37.3	42.7
250	96.9	57.7	24.9	3.2	5.4	45.8	39.2	41.9	47.3
315	95.2	52.8	23.0	3.3	5.3	49.1	42.4	45.1	50.5
400	93.4	48.3	23.1	3.1	5.7	51.5	45.1	47.6	53.0
500	92.8	46.9	24.4	3.0	5.7	52.3	45.9	48.3	53.7
630	90.7	43.4	15.5	2.7	6.4	53.2	47.3	49.2	54.6
800	89.1	41.1	13.3	2.5	6.9	53.6	48.0	49.6	55.0
1,000	88.5	40.2	11.8	2.4	7.2	53.7	48.3	49.7	55.1
1,250	90.0	44.4	11.8	2.2	7.7	50.7	45.6	46.7	52.1
1,600	90.9	48.8	10.2	2.1	8.3	46.9	42.1	42.9	48.3
2,000	88.3	44.7	9.9	2.0	8.8	48.1	43.6	44.1	49.5
2,500	87.8	42.4	7.6	1.9	9.2	49.7	45.4	45.8	51.2
3,150	86.0	39.9	6.9	1.7	10.0	50.1	46.1	46.1	51.5
4,000	84.6	33.7	6.3	1.7	10.4	54.7	50.9	50.7	56.1
5,000	81.5	26.5	6.5	1.5	12.0	58.2	55.0	54.2	59.6
						R'_w	***D_n***	***D_{nw}***	***$D_{nT,w}$***
					Single rating value in dB	**51**	**45**	**47**	**52**

Table 3-2: Single rating values and the calculated spectrum adaptation terms C, C_{tr}, respectively for the measured airborne sound insulation.

Frequency region	**Spectrum adaptation term (dB)**	R'_w **51 dB**	D_w **45 dB**	D_{nw} **47 dB**	$D_{nT,w}$ **52 dB**
100 Hz – 3,150 Hz	C	-2	-2	-2	-2
	C_{tr}	-5	-6	-5	-4
50 Hz – 5,000 Hz	C	-3	-3	-3	-2
	C_{tr}	-12	-14	-12	-11
50 Hz – 3,150 Hz	C	-3	-4	-3	-3
	C_{tr}	-12	-14	-12	-11
100 Hz – 5,000 Hz	C	-2	-1	-1	-1
	C_{tr}	-5	-6	-5	-4

From Tabs. 3-1 and 3-2, it is seen that the highest value is obtained for a weighted standardized level difference of $D_{nT,w}$ = 52 dB, followed by the apparent sound reduction index R'_w = 51 dB. The lowest value is observed for the weighted level difference D_w = 45 dB.

If the respective adaptation term C_{tr} is considered to take the low frequency noise into account, the results presented in Tab. 3-3 are yielded.

Table 3-3: Difference between the single number rating values with C_{tr}-value.

Frequency region	$R'_w + C_{tr}$ (dB)	$D_w + C_{tr}$ (dB)	$D_{nw} + C_{tr}$ (dB)	$D_{nTw} + C_{tr}$ (dB)
100 Hz – 3,150 Hz	46	39	42	48
50Hz - 5,000 Hz	*39*	31	35	41
50 Hz - 3,150 Hz	*39*	31	35	41
100 Hz - 5,000 Hz	46	39	42	48
Diff. (max – min)	7 dB	8 dB	7 dB	7 dB

It is observed in Tab. 3-3 that the maximum values occur for D_{nTw} + C_{tr} = 48 dB in a frequency range of 100 Hz – 3,150 Hz and 100 Hz – 5,000 Hz and that the minimum values occur for D_w + C_{tr} = 31 dB in a frequency range of 50 Hz – 3,150 Hz and 50 Hz – 5,000 Hz.

Overall, a maximum difference of 8 dB is observed in each group of a single rating and of 17 dB between each single value.

From the definition, it is known that the airborne sound insulation describes the reduction of sound. All values are supposed to rate the same construction. Therefore, the single numbers are very useful to present the results and compare products. However, to assess the ability of a building element or building structure in terms of the hearing sensation, the methods described in conventional standards are not sufficient. This is illustrated by comparing the loudness of two sounds. Because loudness depends mainly upon the sound pressure of the stimulus but also upon its frequency, waveform and duration, it is thought to be a prime measure to describe hearing sensation. By definition, one sone is equal to 40 phons and also equal to 40 dB on the equal loudness contours (see section 3.1.3). The basis for the measurement of loudness is the phon. By definition, the loudness level of a 1k Hz tone in phons is its SPL (see Fig. 3-7).

According to the definition in the standards (DIN 45631, 2008; ISO 532, 1975), the loudness of this 1,000 Hz tone (L_{1kHz} in dB) in sones, N, is found by Eq. (3-11):

$$N = 2^{\frac{L_{1kHz}-40}{10}} \qquad (3-11)$$

The loudness function is typically specified for the 1k Hz tone. However, the loudness function can similarly be plotted for other frequencies using equal-loudness contours (Zwicker and Fastl, 1999).

In Tab. 3-4, a conversion of the loudness level in phons and the loudness in sones is presented.

Table 3-4: Comparison of the loudness level in phon and loudness in sone.

Loudness level (phon)	**Loudness** (sone)	**Valuation**
40	1	Equal loud
50	2	Twice as loud
60	4	Four times as loud
and so on		

As was seen in the previous sections, at the threshold of hearing, a sound can only be detected by the human ear if the sound is "loud" enough. In other words the sound can only be heard if the sound is at or above the threshold. At or above the threshold of hearing, the amount of loudness is a subjective interpretation of the sound pressure level of the sound.

Table 3-5 summarises the subjective perception of noise level changes and shows that a reduction in sound energy (pressure squared) of 50% results in a reduction of 3 dB and is just perceptible to a normal ear (Hansen, 2010).

Table 3-5: Subjective effect of changes in sound pressure level. Ref. (Hansen, 2010).

Change in SPL (dB)	**Change in power**		**Change in apparent Loudness for wide band sounds**
	Decrease	Increase	
3	1/2	2	Just perceptible
5	1/3	3	clearly noticeable
10	1/10	10	half or twice as loud
20	1/100	100	much quieter or louder

Recalling the results of the measured sound insulation, as presented in Tab. 3-3, differences of the rating values were observed to be approximately 8 dB, and 17 dB, respectively. This means, in terms of a loudness assessment as was shown in Tabs. 3-4 and 3-5, that, when comparing the results, the impression is created that the perceived sound is roughly twice as loud, though the same design will be judged. This seems an unreasonable result and indicates strongly that standard rating values, such as the weighted sound reduction index or the weighted standardized level difference, respectively, are misleading when used as indications of subjectively perceived loudness.

3.3 Conclusions

The review of the basic theory and calculation methods of airborne sound insulation in this chapter showed in detail how the objective measure can be converted into a single numerical value using current standards. The accuracy between theory and measurements is discussed, and it is shown that some significant deviations, especially at lower frequencies, are observed. The repeatability values reviewed are expected to lie within 1.5 and 4.5 dB and are largest at low frequencies.

Furthermore, it was shown that a round robin test conducted in various European laboratories yielded significant differences for the reproducibility, up to 12 dB at middle-high frequencies.

In that regard, it was concluded that the sound pressure level is not reliable for describing the subjectively perceived size of hearing impression because a change in the sound pressure level of 10 dB is supposed to be assessed subjectively as half or twice as loud.

From the results depicted in this section, it was highlighted that there is an indication that it is difficult to find a single numerical value that corresponds to a subjective related measure to describe an airborne sound insulation value using procedures or calculation schemes of conventional standards.

It is additionally shown that loudness cannot be transformed in a simple way to imply airborne sound insulation. From that discussion, it is concluded that the objective transmission loss or airborne sound insulation as described in current standards does not relate sufficiently to the subjective assessed airborne sound insulation and hence is not able to differentiate adequately in the validation of annoyance or noise nuisance.

4 ESTABLISHMENT OF A LOUDNESS BASED MODEL

In the previous chapter, it was shown that conventional standards do not allow for the evaluation of airborne sound insulation accurately in terms of a subjective measure.

The selection of suitable methods for the calculation of problem-specific features from the appropriate sound signals requires the definition of the test task.

First, it must be set if a purely physical evaluation of signals will be used to solve the problem or if a picture of the subjective sense of hearing in the testing task is necessary.

In this chapter, the objective and subjective measures of relevance for the description of airborne sound insulation are first discussed (section 4.1-4.2), followed by the introduction of the model developed (section 4.3-4.5).

4.1 Objective and Subjective Measures of Relevance for the Description of Airborne Sound Insulation

The measured physical quantities according to the nonlinear processing in hearing must be adapted in the model of the subjective sense of hearing. Because the processing of the signals in the ear consists of a combination of non-linear effects, an approximate solution to the problem is realized via illustration of the fundamental non-linearities of the ear. To distinguish sound pressure changes, the threshold area must differ by approximately 3 dB (Hansen, 2010). At higher sound pressure levels, from approximately 60 dB, differences are perceived for just 2 dB. While the doubling of the acoustic energy (3 dB) is just the distinction limit, a doubling of the subjectively perceived level, however, requires a change of 10 dB (Heckl and Müller, 1994).

Another non-linear effect is the frequency dependence of the sound pressure level, which is just noticeable. Low frequencies as well as high frequencies are perceived only at relatively high sound pressure levels. This frequency behaviour is seen in Fig. 3-9, where the equal loudness contours for different sound pressure levels are depicted. As was observed in Fig. 3-7 at frequencies between 1,000 Hz and 6,000 Hz, the sound pressure level required for perception is minimal. This illustrates that the human ear is not equally sensitive to sound at different frequencies; that is why a frequency weighting network, the "*A*-weighting," was developed in the past (see section 3.1.4). Because the characteristic curve of the frequency weighting of the ear is close to the threshold of hearing most bent (see Fig. 3-7), it flattens with increasing sound pressure level, i.e., the curves become more linear. Other curves were set next to the "*A*-weighting" for low volume level in national and international standards, as was discussed in the previous sections. They differ, however, mainly in their behaviour at low frequencies and represent approximations to the frequency-dependent sensitivity of hearing at higher volume levels. Similarly, frequency changes are nonlinearly perceived by the ear. The distinction threshold for frequency changes at low frequencies up to 500 Hz is between 1.5 Hz and 2 Hz and at medium to high frequencies less than 0.5% of the respective frequency (Heckl and Müller, 1994). The physical measure is the sound pressure level. To relate this physical measure to a psychoacoustical measure, the *A*-weighting is not suitable due to various aspects that have been discussed in prior sections. Calculating meaningful characteristics to describe acoustic criteria requires the use of a combined measure. Indeed, the metric "phon" is a unit that is more practical because it is closer to the sound pressure level, expressed in dB SPL or dB(A), which is used more frequently.

Loudness is a subjective quantity and closely linked to the sound pressure level and hence, closely linked to the frequency and the duration of the sound (Zwicker, 1999). The measure of Loudness is sone.

Stevens (1956) demonstrated that this scale is built from psychoacoustic measurement methods called direct measures, which are based on a procedure asking people what they hear. In general the procedure is that the test person will be presented several sounds with different frequencies and sound pressure levels. The test person then judges the sound and gives a figure proportional to the loudness of each sound. This procedure is time consuming, and therefore some calculation models have been developed in the past.

In order to estimate loudness theoretically, i.e. without conducting psycho-acoustic tests, various models have been proposed in the literature in the last years. The most known methods of calculating stationary sounds, i.e. steady-state sounds, have been proposed by Zwicker (1958) and Moore (1996). These two calculation methods are recognized as standard references.

The model of Zwicker found the way into the German national standard DIN 45631 (1991) and in the International Standard ISO 532 B. Whereas Moore's model led to the American Standard ANSI S3.4-2007 (2007). Since sound is not always stationary, there have been developed two advanced models for calculating non-stationary sounds. In 1999 Zwicker and Fastl (1999) published a model relating to characterise loudness for time varying sounds. Glasberg and Moore (2002) followed in 2002 introducing a further model for calculating loudness from time varying sounds. In the German national standard DIN 45631/A1-2008 a supplement is provided presenting the model for calculating the loudness for non-stationary sounds based on the model of Zwicker and Fastl (1999). The following table summarizes the models and their respective application domains.

<u>Table 4-1</u>: Loudness models and their respective application domain (Genesis, 2014).

Model Function	Steady sound	Time-varying sound	Impulsive Sound
ISO 532B / DIN 45631 (Zwicker et al.)	X	—	—
ANSI S3.4-2007 (Moore et al.)	X	—	—
Zwicker for temporally variable sounds	—	X	—
Moore et al. for time-varying sounds	—	X	—
Boullet - Loudness Model for Impulsive Sounds	—	—	X

Impulsive sound loudness was studied by Boullet (2005). This type of sound is described as a sound whose waveform is characterised by a fast transient phase or a more-or-less long decay phase depending on the sound, i.e. no steady phase (Boullet, 2005). Boullet developed this loudness model to evaluate the global loudness of impulsive sounds. Because this type of sound is not a typical sound characterizing housing noise, this loudness model is not further considered in this research. Schlittenlacher et al. (2001) have found from extended psychoacoustic experiments target values at various levels for the loudness of pink noise. They could show that using the procedure of DIN 45631-1991 yield close results to the subjective evaluations for many technical sounds that are nearly stationary. Fastl et al. (2009) pointed out: "*As the standard meets the experimental output for that many sounds, it can be expected to also determine specific loudness very well. The standard DIN 45631 seems to represent a good model for the main loudness within a critical band*". In contrast, the outcomes of ANSI S3.4-2007 yielded results which were too high for all tested sounds, which is an indication for the need of further modification (Schlittenlacher et al., 2001). Furthermore, Fastl et al. (2009) reported: "*for pure tones at 1 kHz with different levels, the loudness values from ANSI S3.4-2007 or DIN 45631-1991 are essentially the same. However, for pink noise of different levels, ANSI*

S3.4-2007 gives systematically higher loudness values than DIN 45631-1991". They also stated that DIN 45631/A1-2008 can be used for assessing many technical sounds, as well as speech and music, which are typically time-varying sounds produce time-varying loudness functions. In addition to spectral effects, temporal effects such as post masking or temporal integration are also assessed in line with features of the human hearing system (Fastl et al., 2009). Fastl et al. (2009) recommended: "*loudness calculations according to the standard DIN 45631/A1-2008 for technical sounds because the loudness-time functions reflect temporal variations important for annoyance studies as well as questions of sound engineering and sound quality design"*.

In this research, the German standard DIN 45631 is used to calculate loudness. For this research the software used was ArthemiS V11 from HEAD Acoustics GmbH which has implemented DIN 45631/A1-2008.

4.2 Description of the Level of Interest

As was illustrated in the previous sections, one of the main objectives in building acoustics is the prediction of transmission loss or airborne sound insulation. This is especially important to control the quality of sound protection. The measurement and the prediction of airborne sound insulation are basically objective measures relying on physical measures and are standardized in various national and international standards. However, the objective measure of airborne sound insulation using techniques as given in standards are in practical cases not in agreement with subjective assessments. This was demonstrated in the previous chapters.

This chapter summarizes the objective metrics and discusses subjective related results on the basis of reported studies in the literature.

4.2.1 Objective Measure to Describe the Level of Interest

As reviewed in the previous sections, airborne sound insulation is essentially the level difference of a sound signal after being transmitted through a partition.

In free space, with a partition separating two domains, the sound reduction index *R* is identical to the sound pressure level difference, *D:*

$$R \equiv D = L_1 - L_2 \text{ dB} \quad (4\text{-}1)$$

L_1 and L_2 are the average sound pressure levels in the source and receiving room, respectively.

Equation (4-1) indicates that the sound signal being transmitted through a partition is strongly related to the airborne sound insulation. This transmitted signal, if detectable, relates to the construction, which acts as a filter to the signal and cannot, as Bradley has shown (Bradley, 1983), be easily masked by a self-generated noise.

The level of interest is, therefore, L_2. This is the sound pressure level that is impinging on the ear of a resident, and thus this level has to be judged correctly in an objective manner relating to a subjective measure.

In real rooms, another approach to derive a level difference is suggested. As shown in section 3.1, the description of the level difference is:

$$D_{nT} = L_S - L_R + 10 \log (T/0.5 \text{ s}) \text{ dB} \quad (4\text{-}.2.1)$$

Supposing the reverberation time in the receiving room is 0.5 s, which is common in residential premises as reported by Lang et al. (2006), the level difference can be written as

$$D_{nT} = L_S - L_R \equiv L_1 - L_2 \text{ dB} \quad (4\text{-}2.2)$$

This simple approach was also chosen by Vorländer (2006) to generate an acoustic filter (equalizer) from the level difference and to neglect the room acoustical properties in the receiving room for auralization reasons. The evaluation of a sound emanating from a neighbouring room through a partition to determine the airborne sound insulation requires a measurement to determine the sound pressure level in the receiving room. It is common practice to take SPL readings to measure that sound level.

The measurement of the sound pressure level is the measurement of the sound strength on a logarithmic scale, comparing the power of the sound level to a reference value. The respective reference value for the sound pressure level is related to a pressure variation of 20 µPa, which is close to the threshold of hearing. The sound level meters that are typically used to measure the sound commonly have the ability to measure the sound with a weighting network labelled as dB(A).

The *A*-network that measures in dB(A) is the most common weighting used today. This concept has already been presented in a previous section (see section 2.4).

What must be noted, however, is that previous studies (Scharf, 1978; Hellman and Zwicker, 1987; Fastl, 1997; Genuit and Fiebig, 2005) have demonstrated that the sound pressure level cannot be judged as an *A*-weighted sound level to represent a proper hearing sensation. Therefore, an *A*-weighted sound level is misleading when used as an indication of subjectively perceived loudness (Zwicker and Fastl, 1999; Fastl, 2006).

Thus, to assess the sound level of interest, i.e., L_2, the loudness level (L_N) is introduced. The sound pressure level (L_2) contains all the information of the airborne sound insulation (R_w, D_{nT}) because it is the transmitted sound signal. Hence, conversion of the sound pressure level into a loudness level yields a sensation level. This will be discussed in the following section.

After the transmission of L_1 through a structure or partition, the sound heard by a listener is L_2. Because the phon is a unit of perceived loudness level (L_N), which is a subjective measure of the strength of a sound, the measure of sound insulation may therefore be written in terms of a loudness level. Thus, it is assumed that the heard sound, which is the sound level of interest (L_2), can be assessed in terms of a loudness level L_N.

The transformation follows the routine of ISO 226:

$$L_2(f) \rightarrow L_N(f) \tag{4-3}$$

The filtered level (L_2) contains all information of the airborne sound insulation characterised by the weighted apparent sound reduction index (R'_w) as it is the transmitted sound signal. Thus, conversion of the sound pressure level into a loudness level yields a sensation level of the sound level of interest.

The loudness is determined by means of a hearing-related measurement procedure focused on the functioning of human hearing. Here, the signal processing units of human hearing (critical bands), as well as the temporal and spectral mask effect, are taken into account.

First of all, airborne sound insulation has to be defined to investigate the sound pressure level of interest. In an idealised way, the frequency-dependent airborne sound insulation was chosen in accordance with the standard ISO 717-1. This is done exemplarily for different R_w-values of 20, 40, and 60 dB. As an example in the left panel of Fig. 4-1, the investigated idealised airborne sound insulation is shown for the case of an R_w-value of 40 dB.

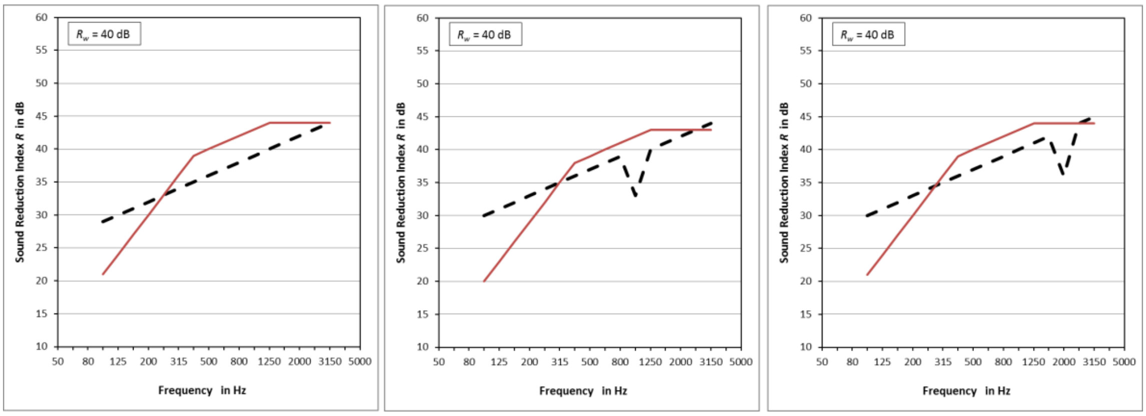


Figure 4-1: Idealized airborne sound insulation exemplarily for R_w = 40 dB without (left panel) and with a dip of 6 dB at the exemplarily depicted frequency of 1k Hz (middle panel) and 2k Hz (right panel). The solid line is the reference curve given in ISO 717-1.

In Fig. 4-2, the computed sound pressure level and the corresponding loudness level for different R_w-values and different sound samples are depicted. The different signal types have been selected due to their different properties, i.e. the envelope of the specific fluctuation strength was chosen as the distinction criterion (ref. chapter 4.4). The steady-state signal was the broadband noise signal “pink noise”, which is according to investigations published in (UBA Wien,2000), most preferable as a substitute for music-type signals if a test signal has to be judged. The non-steady-state signal was a music sample, namely rap (Eminem, “Loose Yourself”). This music type was chosen because investigations (ref. to chapter 5.2) have shown that this piece of music was judged subjectively louder than other music samples compared, such as classic music (Beethoven), otherwise having the same sound pressure level.

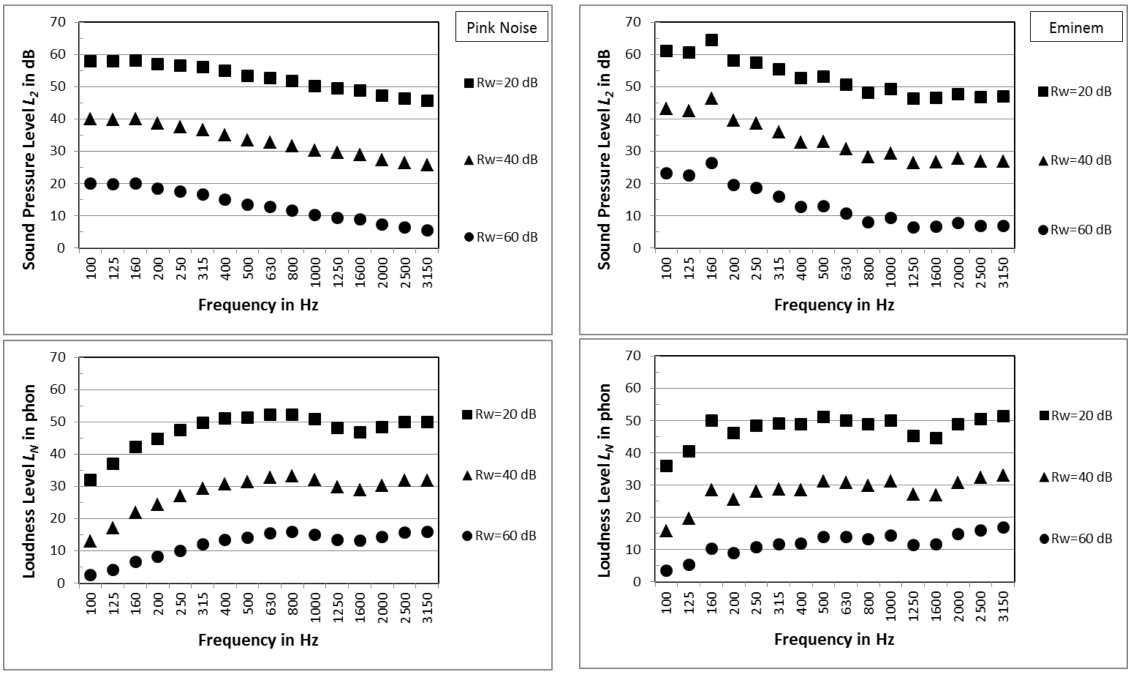


Figure 4-2: Comparison of calculated level after transmission for different R_w-values of 20, 40, and 60 dB using sound pressure level (L_2) and loudness level (L_N). Filter function without a dip.

It is seen from Fig. 4-2, as expected, the sound pressure level after transmission falls off with increasing frequency. This occurs independent of the type of signal and of the R_w-values.

When comparing the loudness level of the same signal, however, the opposite pattern is observed, where, with increasing frequency, the loudness level tends to rise. It is interesting to note that, although the sound pressure level falls off with increasing frequency and increasing airborne sound insulation, the loudness level rises, which was not expected. Computing the level difference of both measures, i.e. the difference of the sound pressure level (L_1 - L_2) and the difference of the loudness level ($L_{N1} – L_{N2}$), yields the results depicted in Fig. 4-3. The level differences shown correspond to pink noise and Eminem sound signals. In the filter function for simulating the airborne sound insulation, no dip was introduced.

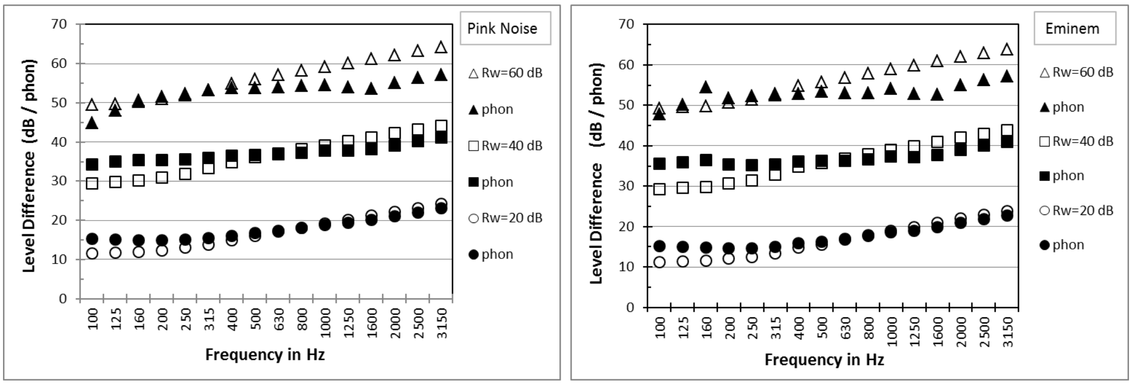


Figure 4-3: The calculated sound pressure level difference ($L_1 - L_2$) and loudness level difference ($L_{N1} - L_{N2}$) over frequency for two types of test signals and various R_w-values without a dip. Shown is the music type signal "Eminem" and the broadband noise type signal "pink noise".

As seen in Fig. 4-3, the smallest difference is observed for airborne sound insulation at midrange frequencies. This means that, at midrange frequencies, the airborne sound insulation expressed as a sound pressure level difference and the airborne sound insulation expressed as a loudness level difference is small. It is notable that, for high frequency and high airborne sound insulation (R_w = 60 dB), the level difference spreads as the frequency rises. For small and medium levels of airborne sound insulation, the opposite pattern is observed, i.e. at low frequency, the differences between both values are greater, and, for higher frequencies, the differences become smaller. This is independent of the type of signal. In addition, it is seen from Fig. 4-3 that, at 100 Hz and for high sound insulation (R_w = 60 dB), the loudness level difference is lower than the sound pressure level difference. This is because the loudness function becomes much steeper at low levels than that at mid and high levels. At high airborne sound insulations, the loudness level becomes smaller, and hence the loudness level difference becomes greater than that for low airborne sound insulation.

4.2.2 Subjective Measure to Describe the Level of Interest

Even after almost a century of research, there is still quite limited knowledge regarding how to describe and evaluate airborne sound insulation in terms of a subjective measure. A comparison of results from several studies in the literature indicate that objective parameters correlating with subjective evaluations differ depending on the stimuli (Gade, 2013).

There are many studies that have examined the objective evaluation of acoustic insulation, i.e., the measurement of airborne sound insulation, accompanied with subjective tests using questionnaires. For example, Langdon et al. (1981) published results of a survey where residents of attached houses were interviewed. This study was conducted in the sequence of a national survey investigating annoyance issues caused by noise from neighbours. As an outcome of that survey it was found that 2/3 of the respondents heard noise from their neighbours (Langdon et al. 1981). Nearly 50% did so even when the sound insulation fulfilled or exceeded the minimum requirements of the Building Regulations. Another outcome was that about 18% of the total sample were seriously bothered by their neighbours' noise. These results, as Langdon et al. (1981) stated "*provide empirical validation of the U.K. performance rating procedure and, these results indicate the importance of sound insulation to occupants of recently built houses, placing this aspect of design and construction within a wider context.*"

Another survey of the indoor sound environment in newly built Swedish residential houses was conducted in the early 1980s, and results were published by Bodlund and Eslon (1983).

The results show that more than 20% of the respondents rate the performance as bad or quite bad. At the same time, however, 51% rate the performance as good or very good. The conclusions drawn from that survey were that there is a low correlation between measured and subjective response for lightweight structures. The same measured sound insulation rating results in different scores for the subjective evaluation, mainly due to low frequency behaviour. They suggested that there is a need for sound insulation down to 50 Hz and that low frequency noise is important, especially for wooden constructions.

At that time, Bradley (1983) also reported results of a survey conducted in Canada. The survey was presented as a building satisfaction survey, and initial questions made no mention of noise or acoustical problems. After each successful interview, permission to make acoustical measurements at a later date was requested. The main result of this study was that the correlations of responses and individual 1/3 octave transmission loss values revealed that significant correlation coefficients are generally found only in the approximate region of 100 to 1,000 Hz, while correlations were strongest from 125 to 400 Hz. He summarized that the reason for this appears to be that it is only in this 100 Hz to 1,000 Hz frequency region that, on average, subjects will hear their neighbours. This is in line with findings by Fasold (1959) in the late 1950s.

Grimwood (1997) published a paper in which he presented the findings of a small study, undertaken in England and Wales between April 1992 and March 1994. In that study he investigated complaints regarding poor sound insulation between dwellings. His findings support previous findings from other researchers that the main noises heard by complainants are, for example, music, television, radio, and voices. Among other results, he stated that the survey indicates that some people are dissatisfied even when their home meets the intended standard. That is, the standard of sound insulation (from section 3 Approved Document E)[*)] for walls is

$$D_{nT,w} \geq 52 \text{ dB}.$$

[*)] Department of the Environment, Approved Document E. Resistance to the passage of sound. HMSO, 1992.

Furthermore, Ljunggren and Ågren (2012) reported results of a project in Sweden that dealt with various aspects regarding sound and vibration within lightweight buildings. They measured, for example, airborne sound insulation according to current ISO standards, but in an extended frequency range. This parameter has shown decent correlation to the habitants' subjective opinion of the sound insulation in traditionally designed multi-family houses made of concrete, masonry or other similar heavy homogeneous materials. They stated: "*As the popularity of lightweight block of flats increases it has been noticed that standardised (ISO) measurements, like airborne and impact sound insulation, tend to show different correlation with subjective experiences compared with concrete buildings.*" Overall, they conclude that: "*The main results – how different objective parameters correlate with subjective perception – are still to be waiting for.*"

Additionally, a recent study by Hongisto et al. (2014) determined which standardized single-number quantities of airborne sound insulation best predict the subjective ratings of living sounds. They found that there is a significant difference between different sound types, which emphasized the importance of the sound spectrum. Furthermore, they stated that: "*surprisingly the value: (R_w + $C_{50-3150}$) was only a slightly better predictor of subjective ratings than R_w or STC in case of bass-rich music sounds.*" This is in line with findings in this research (Neubauer and Kang, 2014 a). However, although Hongisto et al. (2014) found evidence of the importance of considering the low frequency content of the signal, they stated: "*This study does not support the inclusion of the 50-80 Hz third octave bands to the single-number quantity to be used for the objective rating the sound insulation against airborne living sounds.*"

There are several other studies investigating the presence of noise problems associated with building technology with objective acoustical measurements. These studies, however, mainly deal with the advantage and disadvantage of extending the frequency range for the rating procedure.

There are tendencies to overcome the difficulties in defining the differences in acoustic quality between dwellings using a more simplified methodology. Such a simplified methodology is e.g. a description of the airborne sound insulation in classes of acoustical comfort.

These kind of defining classes was proposed in a report of the European Commission (D. E. Commins et al., Report No. 7r, EEC Commission, Brussels, 1976).

However, describing certain subjective impressions of noise protection in different classes and quantifying appropriate values in well-known acoustic indices are not suitable to describe a sensation event such as annoyance, nuisance, or even noise awareness (Kuerer, 1997). This type of classification completely suppresses the spectral components of the signal and any statements made regarding which sound type is assessed.

To summarize this section, it is difficult and often ambiguous to define subjective measures to describe the level of interest with different noise types and different frequency ranges of rating systems. The result of a survey depends highly on the survey method, design, and data analysis.

4.3 The Normalised Loudness Level Difference

The level difference characterised by the weighted sound reduction index (R_w) without a dip (L_0) and with a dip (L_m) provides a set of loudness level differences.

The level difference of the idealized (i.e. hypothetical or computed) airborne sound insulation for third-octave bands is given by Eq. (4-4):

$$\Delta L_{0(f)} = L_{N1(f)} - L_{N2(f),0} \tag{4-4}$$

The level L_{N1} is the frequency depending loudness level in the source room and L_{N2} is the frequency depending loudness level in the receiving room.

The idealised airborne sound insulation to obtain ($L_{2,0}$) may be found using a prediction model as provided by e.g. EN 12354, or by assuming a reference curve e.g. ISO 717-1.

The level difference of an actual (i.e., measured or simulated) airborne sound insulation for third-octave bands is given by Eq. (4-5):

$$\Delta L_{m(f)} = L_{N1(f)} - L_{N2(f),m} \tag{4-5}$$

where $L_{N2,m}$ is the loudness level in the receiving room obtained by the measured or simulated sound pressure level.

In evaluating a sound event, the role of absolute level or loudness is often insignificant. Temporal structures and spectral patterns are more important factors in determining whether a sound makes an annoying or disturbing impression (Sottek and Genuit, 2005).

Therefore, in this thesis it is suggested to normalise the level difference with respect to the idealised level difference.

The normalized level difference with respect to the idealized level difference for third-octave band values is then:

$$L_{nor}(f) = \frac{\Delta L_{m(f)}}{\Delta L_{0(f)}} \tag{4-6}$$

This frequency depending measure may be written as a single numerical value. A method for determining a single value of a sound in terms of a loudness level is given in ISO 532 B, and in DIN 45631, respectively. A loudness level can be measured for any sound and was created to characterize the loudness sensation for these sounds (Zwicker and Fastl, 1999).

The single number quantity for the normalized loudness level difference (L_{nor}) is written as the quotient of the differences of the total loudness levels, yielding:

$$L_{nor} = \frac{L_{N1} - L_{N2,m}}{L_{N1} - L_{N2,0}} \tag{4-7}$$

The calculated normalised loudness level difference as a function is exemplarily for two different sound samples shown in Fig. 4-4.

For comparison, the sound pressure level difference (L_1 - L_2) over frequency is depicted in Fig. 4-5 for two types of test signals. It is seen that the sound pressure level difference rises with frequency and the dip of 6 dB at the frequency of 1k Hz is, similar as for the normalised loudness level difference depicted in Fig. 4.4, observed. What is obvious in both Figures is that there is no difference between the two sound samples.

In summary, the level differences do not distinguish between the two different sound samples but do reflect the event of the introduced frequency dip.

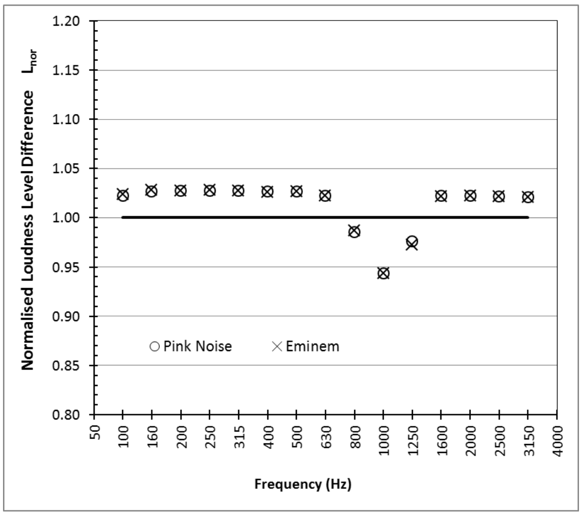


Figure 4-4: Normalised loudness level difference over frequency according to Eq. (4-6) for two types of test signals. Investigated airborne sound insulation with a weighted apparent sound insulation value R_w = 40 dB with a dip of 6 dB at a frequency of 1k Hz.

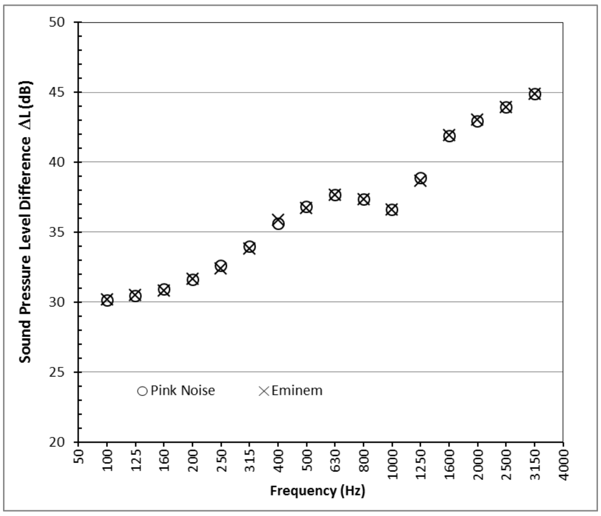


Figure 4-5: Sound pressure level difference over frequency for two types of test signals. Investigated airborne sound insulation with a weighted apparent sound insulation value R_w = 40 dB with a dip of 6 dB at a frequency of 1k Hz.

4.4 The Weighting

It is assumed that a suitable weighting that reflects the event of a frequency-dependent dip must be applied. The weighting will be judged as an awareness of noise, i.e. annoyance.

Therefore, the value is highlighted according to its importance for the comparator or weakened. It is known that psychological effects such as annoyance cannot be fully evaluated by the measurement of the sound pressure level (Kitamura et al., 2002). For this reason, some psychoacoustic factors, such as roughness, fluctuation strength and tonality, were investigated, and it was found that white noise yields a zero value for roughness and tonality for high sound insulation (Neubauer and Kang, 2012 a). This result led to the conclusion that roughness and tonality are not suitable predictors for a rating procedure concerning sound insulation.

In contrast to the psychoacoustic measure roughness, the specific fluctuation strength has modulation frequencies approximately 4 Hz and plays a vital role in the assessment of human speech. This will be detected by a listener as time modifications and hence results in a perception of fluctuation strength (Zwicker and Fastl, 1999), as was discussed already in the previous section in Chapter 3.

From reasons discussed above and because the specific fluctuation strength, *Fls'* (vacil) relates to the temporal structure of the sounds (Schöne, 1979; Zwicker and Fastl, 1999), this measure is preferred to be an appropriate weighting.

To differentiate the signal in terms of psychoacoustic measures, investigations of music type signals were focused on specific fluctuation strength, as was suggested in, e.g. (Neubauer and Kang, 2011 a; 2012 b). This is in accordance with investigations concerning indoor acoustic comfort by Jeon et al. (2011).

The weighting (w) for third-octave band values is the proportion of the frequency-dependent specific fluctuation strength of the signal being transmitted through an idealized (i.e. hypothetical) partition, $Fls'_{(f),0}$, and the specific fluctuation strength of the signal being transmitted through an actual (i.e. measured) partition, $Fls'_{(f),m}$, respectively.

The weighting (w) is given by Eq. (4-8):

$$w_{(f)} = \frac{Fls'_{(f),m}}{Fls'_{(f),0}} \tag{4-8}$$

The total specific fluctuation strength is calculated as the sum of all partial fluctuation strength yielding Fls'. The single number quantity of the weighting (w) is then:

$$w = \frac{Fls'_m}{Fls'_0} \tag{4-9}$$

The calculated specific fluctuation strength as a function of frequency is shown for two different sound samples in Fig. 4-6. As a distinction criterion, the envelope of the specific fluctuation strength is shown and marked in the figure. The chosen music-type signal and the broadband noise signal are shown, where the specific fluctuation strength of the respective signal is shown before filtering.

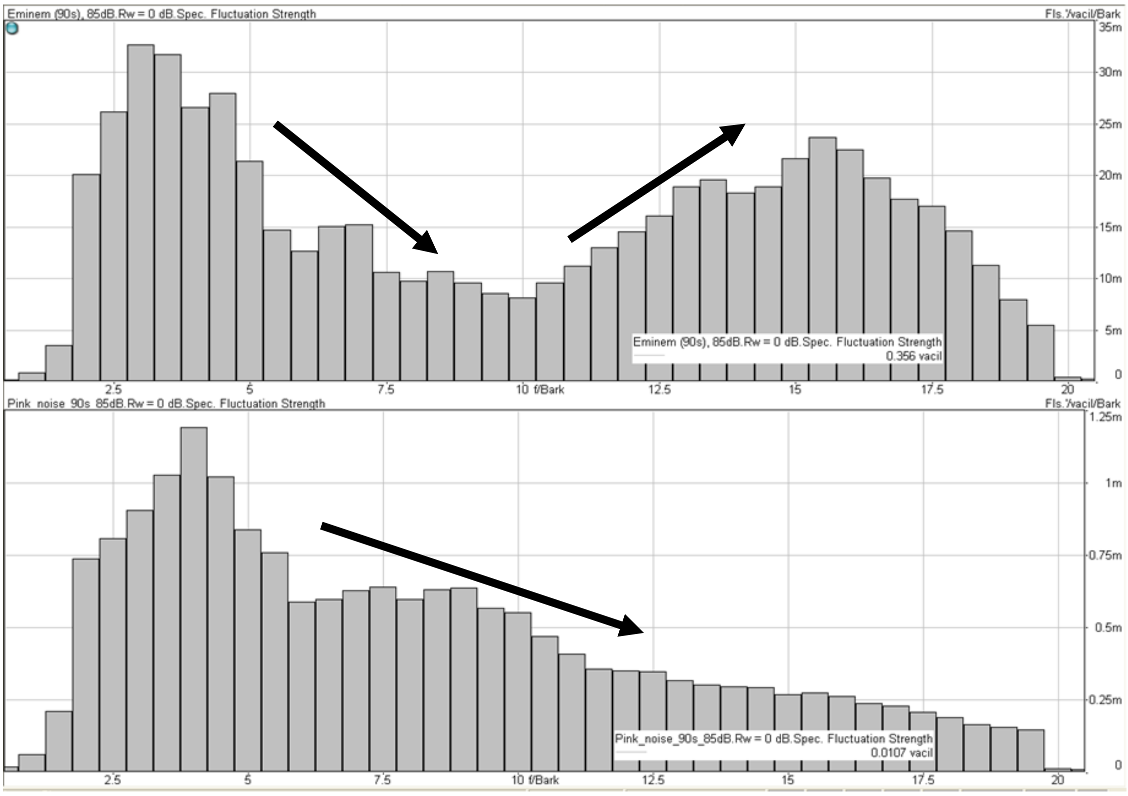


Figure 4-6: Specific fluctuation strength of the unprocessed sound signal “Eminem” and “pink noise”.

The unprocessed music type signal “Eminem” has a specific fluctuation strength of 0.36 vacil, and pink noise has a value of approximately 0.011 vacil. From the comparison, it can be observed that the envelope of the specific fluctuation strength of pink noise falls off with increasing frequency, and, for the signal “Eminem,” the envelope first falls off and then rises again with increasing frequency.

It is noted that Eq. (4-8) as well as Eq. (4-6) are normalised using the level difference characterised by the weighted apparent sound reduction index (R'_w) without a dip in the airborne sound insulation curve. The computed weighting coefficients as a function of frequency are shown in Fig. 4-7. There, two types of test signals are exemplarily depicted, with a weighted apparent sound insulation value of R_w = 40 dB having a dip of 6 dB at a frequency of 1 kHz.

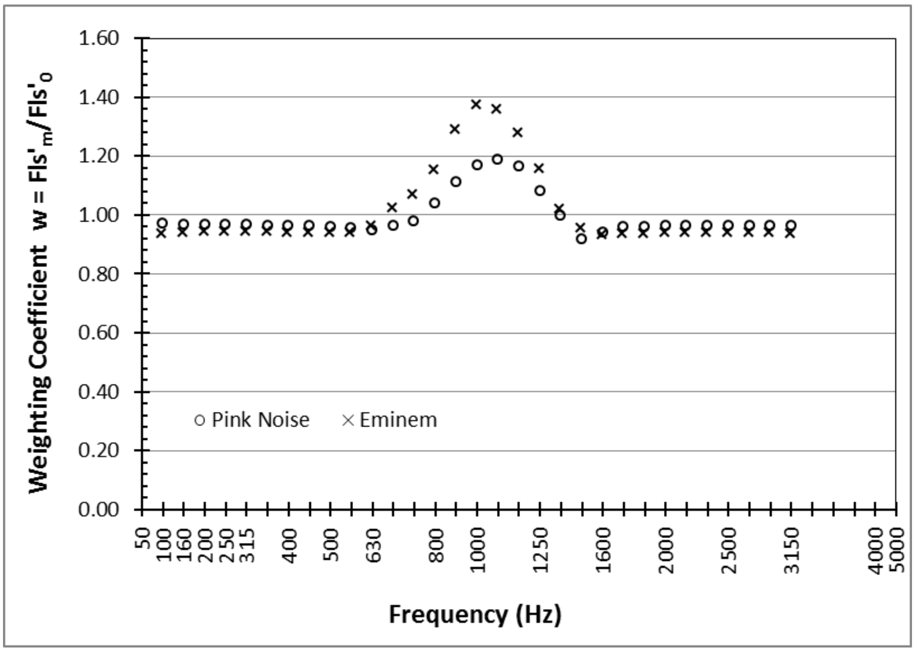


Figure 4-7: Function of the weighting coefficient (*w*) over frequency for two types of test signals according to Eq. (4-8). Shown is the music type signal “Eminem” and the broadband noise type signal “pink noise” for a weighted apparent sound insulation value R_w = 40 dB with a dip of 6 dB at a frequency of 1k Hz.

It is seen from Fig. 4-7, the frequency dip is clearly displayed. For the transient signal, the peak of the function is more formed than for the broadband noise signal. It is noted, however, that the signal “Eminem” displays a higher peak value than the compared “pink noise” broadband signal. Furthermore, it is noted that the signal of the broadband noise displays slightly higher values than the transient signal outside the circle of influence of the dip. That is, the weighting coefficient of the broadband noise is closer to 1 than that of the transient signal.

This is in line with the basic theory of fluctuation strength, which states that unmodulated broadband noise does not have high fluctuation strength.

The circle of influence of the dip at 1k Hz is in the range of 630 Hz to 1.6k Hz. The pink noise signal is shown to be up to approximately 2% above the value of the transient signal "Eminem." At the ambit of the dip at 1k Hz, the transient signal is approximately 9% higher than the broadband noise signal. This makes it clear that the signal type affects the weighting coefficient. It is interesting to see that the signal "Eminem" reaches an approximately 15% higher maximum at the dip event than the signal "pink noise."

To summarise the results up to this point, it is understood that the weighting coefficient reflects the frequency-dependent event in the frequency-dependent airborne sound insulation, and it differs for different types of signals.

4.5 The Weighted Normalized Loudness Level Difference

The loudness model describes the frequency-dependent airborne sound insulation yielding the weighted normalized loudness level difference.

For third-octave band values expressed as the product of the frequency-dependent normalized loudness level difference and a frequency-dependent psychoacoustic weighting factor, the corresponding formula is given in Eq. (4-10):

$$L_{nor,\,w}(f) = L_{nor(f)} * w(f) \tag{4-10}$$

where $L_{nor(f)}$ is the normalized level difference and w is a weighting factor.

Combining Eq. (4-7) and Eq. (4-9) yields the single number quantity for the weighted normalized loudness level difference ($L_{nor,\, w}$) and is written as:

$$L_{nor,\, w} = L_{nor} * w \tag{4-11}$$

Equation (4-11) is case sensitive, i.e., $L_{nor,\, w}$ depends on the individual results of the level differences and the weighting, as is seen from Eq. (4-7) and Eq. (4-9). The following regions occur depending on the six conditions:

I) $L_{nor} > 1 \wedge w > 1 \Rightarrow L_{nor,w} > 1$

II) $L_{nor} < 1 \wedge w < 1 \Rightarrow L_{nor,w} < 1$

III) + IV) $L_{nor} > 1 \wedge w < 1 \Rightarrow L_{nor,w} < 1 \vee L_{nor,w} > 1$

V) + VI) $L_{nor} < 1 \wedge w > 1 \Rightarrow L_{nor,w} < 1 \vee L_{nor,w} > 1$

NB: The region yielding $L_{nor,w} = 1$ needs: $L_{nor} = 1 \wedge w = 1$ and that requires: $L_{2,m} = L_{2,0} \wedge Fls'_m = Fls'_0$. This condition is impossible in real buildings and in real situations in-situ.

The calculated weighted normalised loudness level difference as a function of frequency is shown for an airborne sound insulation of 40 dB with a dip at 1k Hz and for two different sound samples in Fig. 4-8.

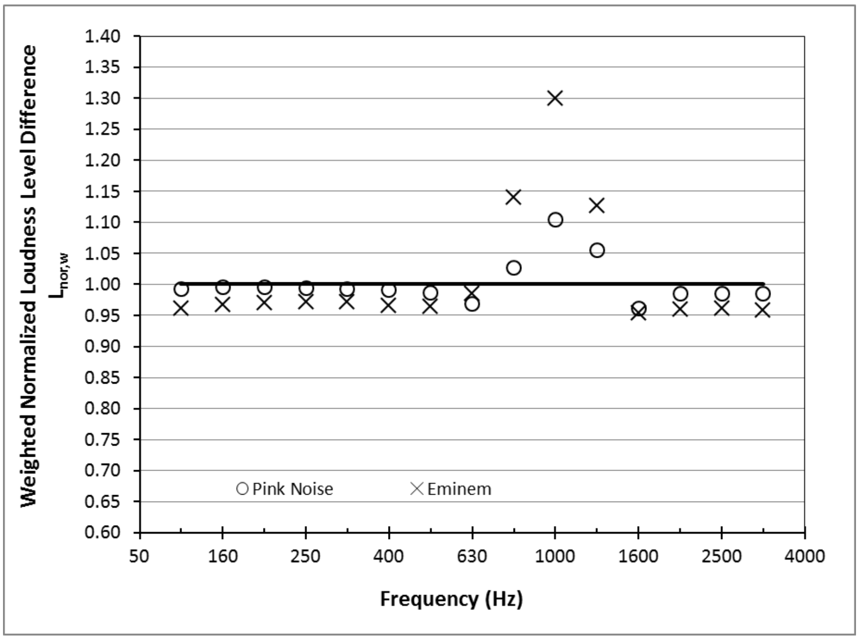


Figure 4-8: Function of the weighted normalised loudness level difference over frequency for two types of test signals according to Eq. (4-10). Shown is the music type signal “Eminem” and the broadband noise type signal “pink noise” for a weighted apparent sound insulation value R_w = 40 dB with a dip of 6 dB at a frequency of 1k Hz.

The introduced dip at a frequency of 1k Hz is clearly seen, and, for the transient signal, the peak is more formed than for the broadband noise signal. Both signals, however, yield similar results outside the ambit of the dip at 1 kHz, i.e. at frequencies below and above that dip, $L_{nor, w}$ is close to 1. In fact, the pink noise signal is up to nearly 3% above the value of the transient signal “Eminem.” That is, no substantial difference is observed in the frequencies of at least one-third octave band off the introduced dip compared to the event of the frequency dip.

The circle of influence of the dip at 1k Hz is again between 630 Hz and 1.6k Hz. It is clearly seen that $L_{nor, w}$ is constant and close to 1 except at frequencies around the ambit of the introduced dip.

In the case of Fig. 4-8, this is approximately 1 kHz with a spread of approximately one-third octave bands. The music type signal reveals again a higher peak value than the broadband noise signal. The signal “Eminem” reaches an approximately 15% higher maximum value at the dip event than the signal “pink noise.” The average value of $L_{nor,\,w}$ for the Eminem signal is 1.01 with a standard deviation of 0.10, and, for pink noise, the average is 1.00 with a standard deviation of 0.04.

4.6 Conclusions

This chapter introduced a novel calculation scheme of a loudness-based model. Through analysing psychoacoustical parameters and conventional standards, it was reviewed that a subjective rating in conjunction with an objective measure has not been done before. It has been shown that it is feasible to transform the objective measure of a sound pressure level into a loudness level and form, together with the specific fluctuation strength, a subjectively related evaluation. This new measure of a weighted normalized loudness level difference permits evaluating a construction in terms of an objective and subjectively related measure.

5 VALIDATION AND IMPLEMENTATION OF THE LOUDNESS BASED MODEL

The introduced model is validated in this chapter to show how the model works with different parameters, such as different test signals, airborne sound insulation values, and psychoacoustic measures. The results shown in chapter four are implemented showing the validity of the prediction model (section 4.3-4.5). Finally, it summarizes the main results of the model (Neubauer and Kang, 2011 a, 2012 a, 2013 b, 2014 a, b, c, 2015 a, b).

5.1 Test Signals

Building acoustic measurements require a specific sound source. The sound source must radiate sound evenly in all directions to give reproducible and reliable results. The relevant standard describing building acoustics measurement related to airborne sound insulation measurements (ISO 16283) requires the use of an omnidirectional sound source fed by random noise (B&K, 2014).

5.1.1 Compliance with the Standards

Airborne insulation tests, which are conducted on new and converted dwellings or even in laboratories to test a material or construction, provide meaningful results when they are independent of who measures the sound insulation. Hence, all testers must use the same standards. This requires compliance with ISO 16283, and ISO 717, and it follows that the scheme must comply with these standards. To test the airborne sound insulation performance of a wall or floor, between two rooms a sound source generating a broadband spectrum of noise at all frequencies must be used. The spectrum should cover at least the frequency range of 50 Hz to 5,000 Hz. The generated sound level in the source room has to be amplified that the level in the receiving room is sufficiently higher above the background noise level. It is common practice to use random noise, such as pink noise or white noise, as an excitation signal as required by the standards. This condition of the characteristics of the signal originates from theoretical considerations regarding transmission theory, which defines equally distributed sound energy in a room where the test is conducted. However, it is proven in this thesis that transient sound signals, i.e., non-noise-type excitation signals, do affect the result in determining the airborne sound insulation, especially the rating according to the standards.

There are other measurement methods, such as the maximum length sequence (MLS) (Vorländer and Kob, 1997) and swept-sine methods (Müller and Massarani, 2001), both of which integrate a measured impulse response to obtain the SPL, in use to measure airborne sound insulation. Compared with noise-type excitation signals, they correspond to measurements with infinite integration time. Furthermore, sweeps can be argued to be superior to pseudo-noise signals, such as MLS, as they exhibit significantly higher immunity against distortion and time variance (Müller and Massarani, 2001, Venegas, et al., 2006).

However, these types of excitation signals have not been considered in this research because the signals do not relate to occupational noise types and do not relate to psychoacoustical magnitudes, such as loudness.

This research addresses sound signals filtered by a construction or partition, and therefore the sound stimulus is of vital interest. It is reported in the literature (Brambilla, et al., 2001) that the subjective preference for a sound stimulus is influenced both by the overall sound energy and by its distribution in the frequency domain. Accordingly, acoustic parameters which are centred on sound energy are not sufficient to characterise sensation in terms of airborne sound insulation measures.

In this chapter, the characteristics of different sound signals and the effect on the assessment of the processed sound signal are studied in more detail.

5.1.2 Objective Measure of the Signals

From basic theory for describing airborne sound insulation (Cremer, 1953; Fahy and Gardonio, 2007; Cremer and Heckl, 1996), it is known that the type of sound signal used as an excitation signal to yield the transmission loss of a partition does not have any influence on the sound insulation of the investigated structure. This is true as long as the objective measure of a sound intensity or sound pressure level is concerned.

However, previous results presented (Neubauer and Kang, 2011 a, 2011 b), revealed that, for different signal types, the subjective impressions of a sound heard are different as well. This was also reported by Ryu and Jeon (Ryu, Jeon, 2011), indicating that indoor residential noise is judged differently from different noise types.

Furthermore, in the literature (Grimwood, 1997; Park and Bradley, 2009; Masovice *et al.*, 2011), it is reported that music is one of the most frequently detected noises, even in dwellings, fulfilling the sound insulation requirements.

Therefore, the influence using different signals is investigated via two categories of signals, namely steady-state and non-steady-state signals. The steady-state signals are the broadband noise signals, "pink noise" (PN) and "white noise" (WN). These signals are chosen because they are recommended in the standards for measuring airborne sound insulation.

Especially according to investigations published in (UBA Wien 2000), pink noise appears to be most preferable as a substitute for music-type signals if a test signal has to be judged.

The non-steady-state signals, i.e. the transient signals, were music samples, namely rap (Eminem: "Loose Yourself") (E) and classic music (Beethoven: Symphony Nr. 9: Poco Allegro, Stringendo Il Tempo, Sempre Piu Allegro - Prestissimo) (B). This type of music was also investigated earlier (Neubauer and Kang, 2011 a, 2012 a, 2013). Additionally, a music type called "Party Sound" was used as a source signal. This sound was a combination of talking and laughing people and dance music. The time spectrums of the used signals are shown in Fig. 5-1.

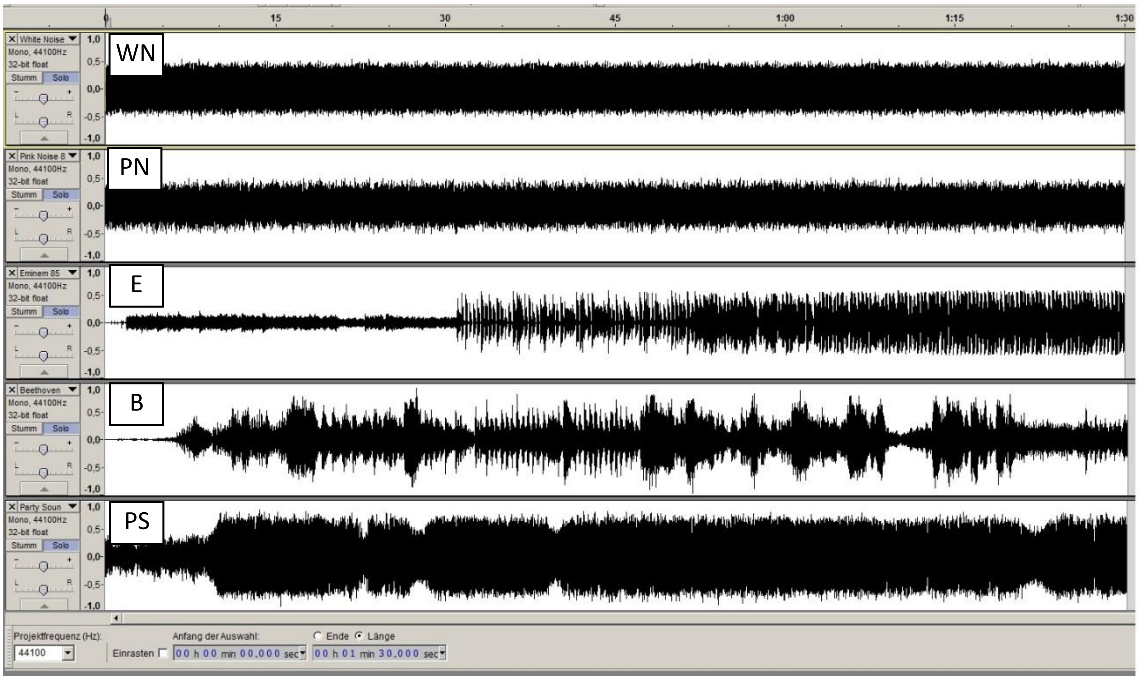


Figure 5-1: Time signal of white noise (WN), pink noise (PN), Eminem (E), Beethoven (B), and Party Sound (PS) with sound pressure level of 85 dB SPL and duration 90 s.

Pink noise, also known as 1/f-noise, is a signal with a frequency spectrum such that the power spectral density is proportional to the reciprocal of the frequency. There is equal energy in all octaves. In terms of power at a constant bandwidth, 1/f-noise falls off at 3 dB per octave.

White noise, in contrast, is a random signal with a flat power spectral density. The signal contains equal power within a fixed bandwidth at any centre frequency.

The power spectral densities of the noise-type signals are depicted for comparison in Fig. 5-2.

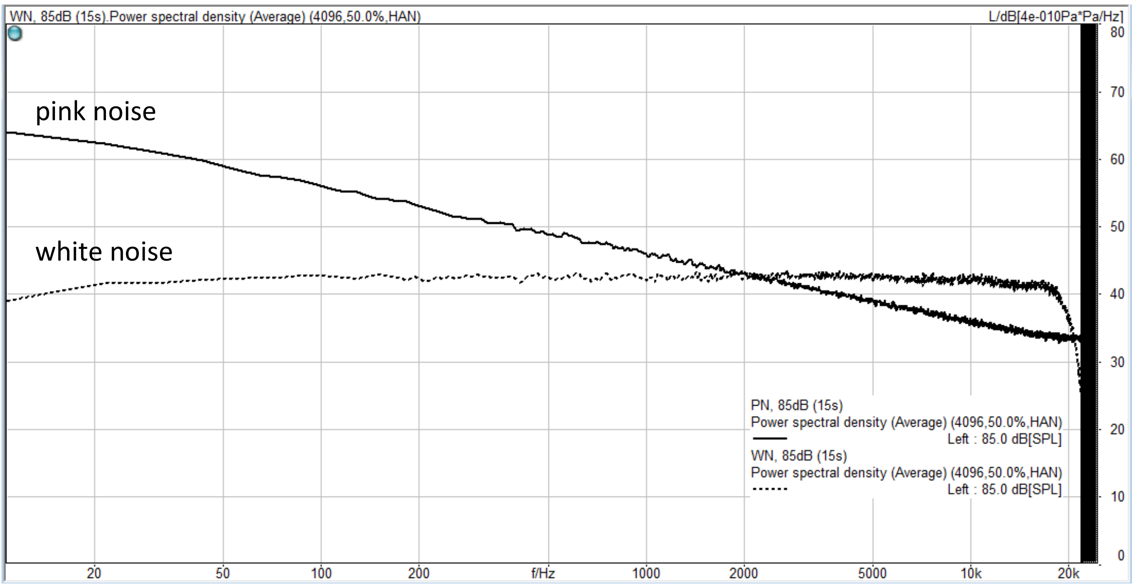


Figure 5-2: Power spectral density (PSD) of steady noises, i.e. pink noise and white noise as a function of frequency. The sound pressure level of the signals is 85 dB and the duration is 15 s.

Figure 5-2 displays a decreasing straight line over the frequency bandwidth for pink noise, while a constant straight line over the frequency bandwidth is seen for white noise.

The non-steady or fluctuating noises used in this study are the music-type signals as described above. The power spectral densities of these signal types are depicted in Fig. 5-3.

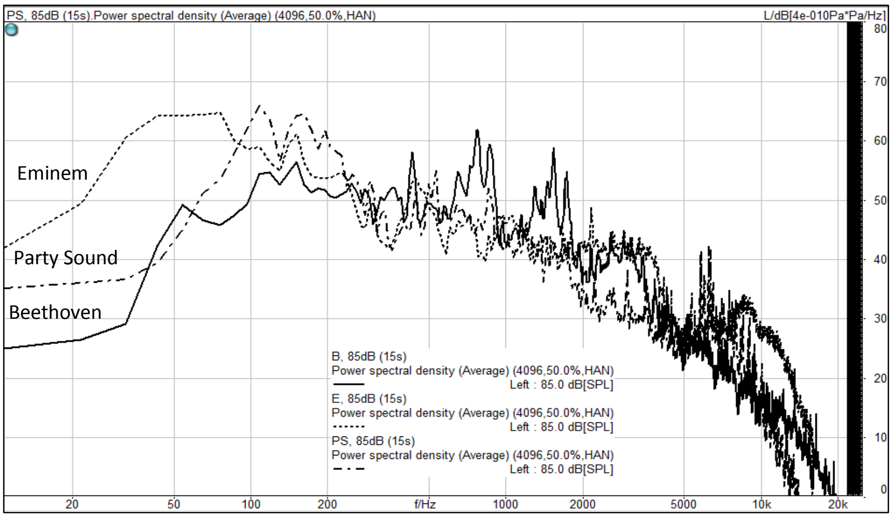


Figure 5-3: Power spectral density (PSD) of non-steady or fluctuating noises as a function of frequency. The sound pressure level of the signals is 85 dB and the duration is 15 s.

The music-type signals show similar patterns over the frequency bandwidth. A steep increase of the power spectral density is observed at low frequencies below a frequency range of approximately 100 Hz and decreasing with a certain fluctuation toward higher frequencies. This is in line with the literature (UBA Wien, 2000) and is exhibited in Fig. 5-4 where different music spectra are shown. In that figure “Rosa Rauschen” indicates “pink noise”.

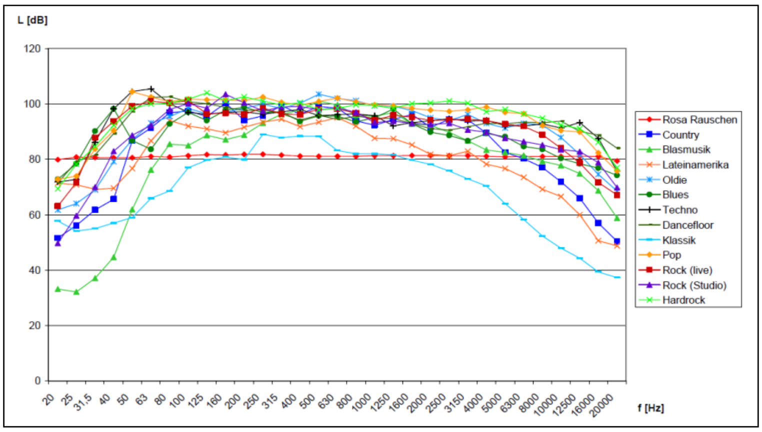


Figure 5-4: Representation of the linear energy equivalent third octave spectra of the output signals of the various music pieces and pink noise (UBA Wien, 2000).

5.1.2 Psychoacoustic Measures of the Signals

To describe a sound event, psychoacoustic measures are commonly used.

Loudness as a measure for hearing sensation is well known, referring to the human perception of sound volume. While sharpness is a hearing sensation related to frequency and independent of loudness, it is supposed to be a measure that can be considered separately and hence can be used to compare different sounds. These elementary auditory sensations, together with roughness, tonality, and fluctuation strength (the latter being an important hearing sensation measurement), are investigated in this section. The psychoacoustic parameters sharpness and tonality are defined in Appendix V,a). For the investigated sound source signals all the aforementioned parameters are calculated and results are listed below in Tab. 5-1.

Table 5-1: Psychoacoustic factors of the unprocessed signals: sound pressure level (L), loudness level (L_N), loudness (N), sharpness (S), specific roughness (R'), tonality (Ton), and specific fluctuation strength (Fls').

Sound sample	*L (dB)*	*L_N (phon)*	*N (sone)*	*S (acum)*	*R' (asper)*	*Ton (tu)*	*Fls' (vacil)*
White Noise	85	98.5	57.6	2.79	3.62	0.0197	0.0166
Pink Noise	85	99.1	60.0	2.14	3.95	0.0170	0.0225
Beethoven	85	97.2	53.7	1.43	3.47	0.181	0.1182
Eminem	85	94.8	45.9	1.60	3.63	0.182	0.223
Party Sound	85	94.8	45.2	1.58	2.90	0.234	0.129

All of the psychoacoustic parameters presented in Tab. 5-1 are additionally calculated using filter coefficients for the idealized sound insulation with R_w-values of 20 dB, 40 dB, and 60 dB and summarized and tabulated for reference in Appendix V, b).

It is observed from data in Appendix V that the specific roughness (*R'*) and the tonality (*Ton*) yield zero values for high sound insulation. These psychoacoustic measures are therefore not considered for further investigations in this study.

If the loudness level (L_N) of the sound signals used in this study is calculated for different sound pressure levels (*SPL*), it is observed that there is no linear correlation between both measures. This is illustrated in Fig. 5-5, where the loudness level is depicted over sound pressure level.

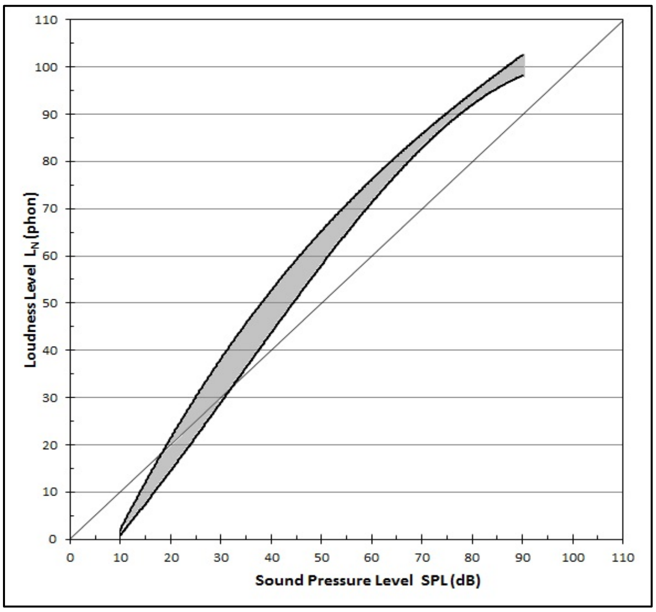


Figure 5-5: Loudness level (L_N) as a function of sound pressure level (*SPL*) for different sound signals including transient and steady state signals. The shaded area characterizes the region for the loudness level (L_N). The straight line corresponds to the relationship: “sound pressure level = loudness level”.

From Fig. 5-5, it is seen that the loudness level is not linearly related to the sound pressure level and is dependent on the type of signal. Even for equal sound pressure level, the calculated loudness level differs in its absolute value depending on the type of signal.

Inspection of these data shows that varying the sound signal, i.e., using a broadband noise signal and a transient signal, leads to somewhat different results, allowing the sound pressure level to remain constant. This means that the loudness of a broadband sound and that of a transient signal are different. This is in agreement with the literature (Zwicker and Fastl, 1999).

For the investigated sound signal of pink noise, it was observed that, at 40 dB SPL and above, the calculated loudness level was always higher than what was calculated for the other sound signals. Below a sound pressure level of 40 dB, white noise and Beethoven yield the highest loudness level values.

To investigate the difference of a measured and simulated signal after transmission through a construction, or filter, airborne sound insulation measurements have been carried out to obtain the receiver level (L_2). This level is supposed to be the receiving level after transmission through a dividing construction between two rooms.

The respective frequency values of this airborne sound insulation ought to be the filter coefficients used to simulate in a computer program the sound insulation of a real construction.

In Fig. 5-6, the measured sound pressure level (L_2) and the calculated loudness ($N_{(L2)}$) for two constructions investigated, i.e., a wall and a door, are depicted using two different source signals, pink and white noise.

The measurements carried out following the procedure of EN 16283-1 yield an apparent sound reduction index of the wall of R'_w = 41 dB and of the door of R_w = 22 dB.

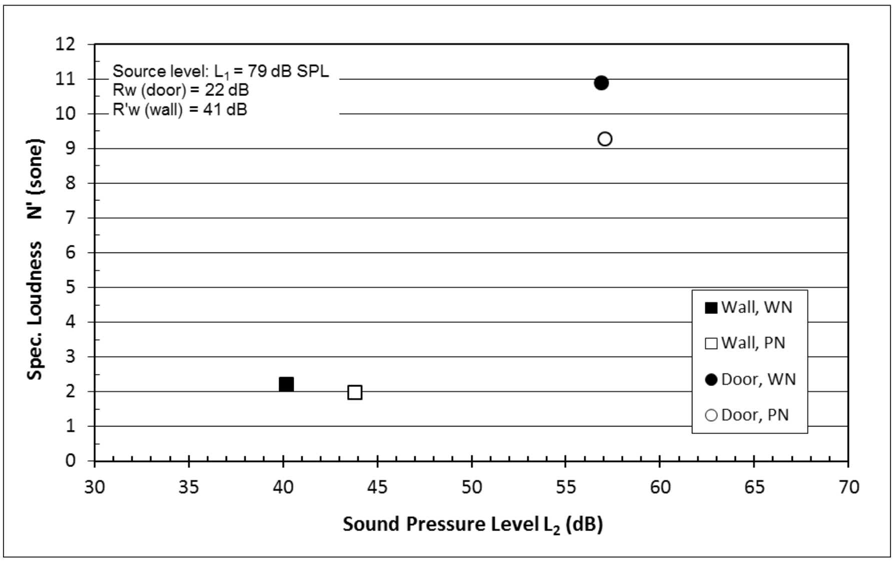


Figure 5-6: Measured SPL (L_2) and calculated loudness ($N_{(L2)}$) for pink and white noise.

It is seen in Fig. 5-6 that the transmission loss measurements of the wall yield different sound pressure levels of the transmitted sound signal, yielding a median of the specific loudness that is 2.09 ± 0.16 sones. For the door measurement, the two source signals yield a greater difference, which yield a median of 10.09 ± 1.15 sones.

Using the measured sound pressure level in the receiving room (L_2) and the obtained frequency-dependent airborne sound insulation (R') as the filter coefficient in a computer program to filter the source signal, both signals, i.e., the measured *SPL* after transmission and the simulated *SPL* after filtering, can be compared to investigate the validity of the proposed method. In Fig. 5-7, the results of the comparison of the measured and simulated results are shown. First, from the measured sound pressure level in the receiving room, the specific loudness was calculated, yielding L_{N2} ($L_{2,\ \mathrm{measured}}$). Second, from the simulated sound pressure level, which was obtained after filtering with the calculated filter coefficients taken from the measured transmission loss, the specific loudness was calculated, yielding L_{N2} ($L_{2,\ \mathrm{calc}}$).

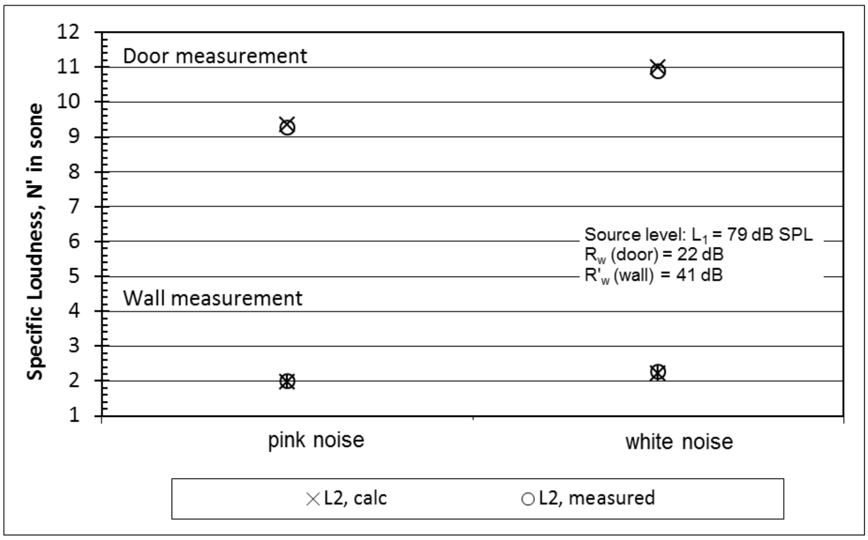


Figure 5-7: Comparison of "measured" and "simulated" loudness (*N*) for pink and white noise.

From Fig. 5-7, it is seen that the computed results are very close to the measured ones. To calculate the error that occurs using the simulated sound pressure level for calculating the specific loudness, Eq. (5-1) was used. The (x_m) values indicate the measured results, and the (x_c) values indicate the calculated ones.

$$err = \left(1 - \frac{x_m}{x_c}\right) * 100\% \tag{5-1}$$

Table 5-2: Calculated error for the loudness calculation using a measured sound pressure level (x_m) and a calculated sound pressure level (x_c).

	Measured			*Simulated*			
	L_1 (dB)	L_2 (dB)	*N'* (sone)	L_1 (dB)	L_2 (dB)	*N'* (sone)	*err (%)*
Door (R_w = 22 dB)							
Pink Noise	78.9	57.1	9.28	78.9	57.0	9.34	0.64
White Noise	78.9	56.9	10.9	78.9	56.9	11.0	0.91
Wall (R'_w = 41 dB)							
Pink Noise	78.8	43.8	1.97	78.8	43.6	2.01	1.99
White Noise	78.3	40.2	2.20	78.3	40.3	2.26	2.65

The calculated error as shown in Tab. 5-2 illustrates that the method to simulate the frequency-dependent airborne sound insulation (R'_w) by using the frequency-dependent R'-values as filter coefficients to build a transfer function in a computer program is a reliable procedure. The calculated error was less than 3%, which confirm that the method yields reliable outcomes. With this method, it is possible to examine any particular sound signal in detail, especially with regards to psychoacoustics. Investigating the filtered signals in terms of the psychoacoustic measure of sharpness (*S*) yields the results depicted in Fig. 5-8.

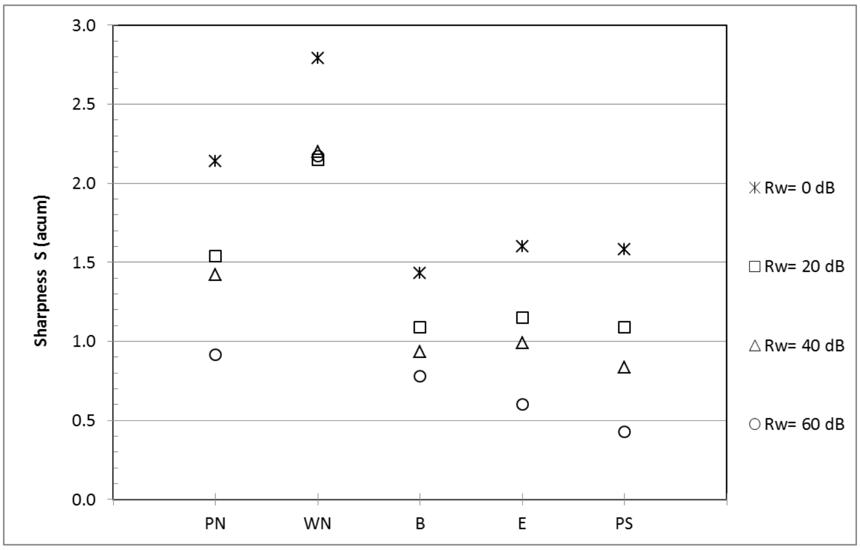


Figure 5-8: Sharpness (*S*) calculated from the receiving sound pressure level after filtering with different airborne sound insulation values and different source signals. All source signals have a sound pressure level of 85 dB SPL.

It is clear from Fig. 5-8 that the unprocessed broadband noise signals of pink noise and white noise yield the highest sharpness. This result is unexpected because sharpness is a measure of the high frequency content of a sound, i.e., the greater the proportion of high frequencies, the greater the *S*-value. However, to assess a construction in terms of a transmission loss, sharpness seems to not be a suitable predictor because typically the airborne sound insulation rises rapidly with frequency. Sharpness is thought of as a measure to assess a signal where the high frequency content is important to a construction's quality. However, this is not a prime aspect for airborne sound insulation. This psychoacoustic measure is therefore not considered for further investigations in this study. The next psychoacoustic parameter to assess a sound signal is the specific fluctuation strength (*Fls'*). The specific fluctuation strength is not a linear function and is dependent on the type of signal and on the level of the sound signal.

In Fig. 5-9, the region of the specific fluctuation strength (*Fls'*) of the sound signals used in this research is depicted as a function of sound pressure level.

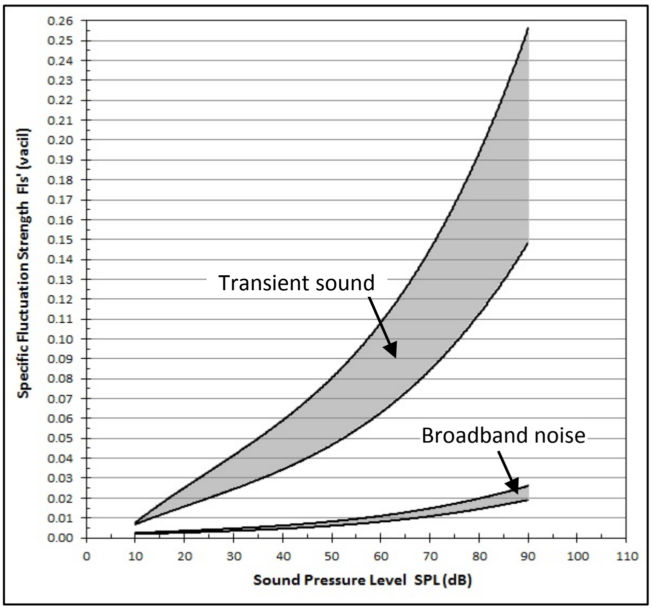


Figure 5-9: Specific fluctuation strength (*Fls'*) as a function of sound pressure level (*SPL*). The shaded area characterizes the region for the specific fluctuation strength (*Fls'*).

It is seen that the broadband noise signal has little specific fluctuation strength, whereas the transient signal, i.e., music-type signal, spreads with increasing sound pressure level. This means that the specific fluctuation strength depends on the level of the signal.

For very low sound pressure levels, i.e., below approximately 10 dB SPL, both signal types tend to gain close to zero. The smallest values are observed using white noise, and the maximum values are identified for the music-type signal "Eminem." The deviation of the studied signal types, i.e., the difference between a broadband noise signal and a music-type signal, was observed to be as large as a factor of approximately 100.

The specific fluctuation strengths (*Fls'*) as a function of frequency of the sound signals depicted in Fig. 5-1 are shown in Fig. 5-10. It is seen that party sound (*PS*) shows a high peak at 200 Hz and declines very rapidly towards higher frequencies. Eminem shows two maxima, the first at approximately 450 Hz and the second at 3,700 Hz. Beethoven shows more maxima, four in total. It is, however, interesting to observe that the Beethoven signal shows "antiphase" with the Eminem signal at mid-frequencies of approximately 600 Hz – 3,000 Hz.

As was also expected, broadband noise signals have only slight fluctuation, with white noise having less than pink noise. This in line with the literature (Aures, 1985) and it confirms results presented earlier (Neubauer and Kang, 2012 b).

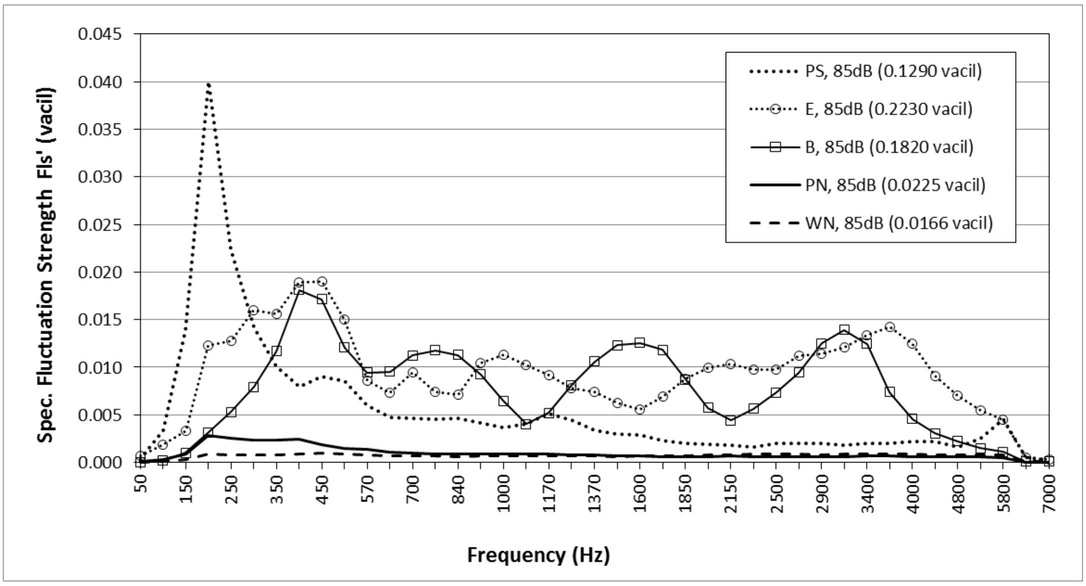


Figure 5-10: Specific fluctuation strength (*Fls'*) as a function of frequency of the sound signals used in this study. The sound pressure level of the signals is 85 dB and the duration is 15 s.

It is of interest to determine how the specific fluctuation strength changes with sound insulation. This change is depicted in Fig. 5-11, where the specific fluctuation strength (*Fls'*) is shown for different sound insulation values and for different source signals. From that figure, it is seen that broadband noise signals do not change much in fluctuation strength, even for high sound insulation. White noise showed the smallest values. It is noted that the transient signals spread for all sound insulation steps, i.e., Party Sound is smaller than Beethoven, and Eminem is the highest. The calculated specific fluctuation strength (*Fls'*) for different sound signals and different R_w-values reveal that transient sound signals, i.e., the music-type signals (Eminem, Beethoven, and Party Sound), have higher values than broadband noise signals (pink and white noise). This was also seen for the unprocessed signals; however, through the filtering process, the signals change, and it is observed that Eminem reveals higher values than previously found for the unprocessed signal Party Sound. The calculated specific fluctuation strength (*Fls'*) for different sound signals and different R_w-values as shown in Fig. 5-11 are shown in Tab. 5-3 numerically.

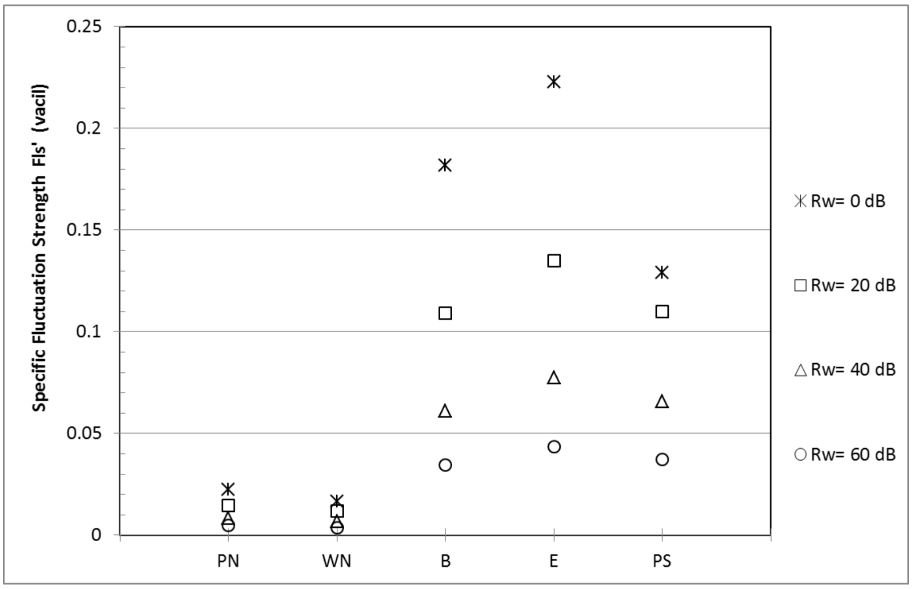


Figure 5-11: Specific fluctuation strength (*Fls'*) calculated for different R_w-values and different source signals. All source signals have a sound pressure level of 85 dB SPL.

Table 5-3: Specific fluctuation strength for different airborne sound insulation values and different source signals. All source signals have a sound pressure level of 85 dB SPL.

Specific Fluctuation Strength, Fls' in vacil				
Airborne Sound Insulation R_w in dB				
Sound sample	0	20	40	60
White Noise	0.00166	0.0120	0.00689	0.00387
Pink Noise	0.0225	0.0148	0.00849	0.00477
Beethoven	0.1820	0.1090	0.06110	0.03440
Eminem	0.2230	0.1350	0.07740	0.04350
Party Sound	0.1290	0.1100	0.06590	0.03710

As was seen broadband noise signals (pink noise or white noise) do not change much in specific fluctuation strength with increasing sound insulation, which is expected, but this could be an indication that transient signals, i.e., non-steady-state signals, can be more influenced with appropriate sound insulation in the sense of subjective judgments to rate the annoyance of the receiving sound between a dividing partition (Jeon et al., 2011).

5.2 Subjective Assessments on Test Signals

Hearing tests were conducted to subjectively assess different test signals at different sound insulation values. The main goal of this investigation was to find evidence that perceived sound is judged differently if the signal is changed or if the spectrum of airborne sound insulation differs. It is therefore vital to understand how the model represents differences in sound signals and spectra and how these differences are related to subjective assessment.

5.2.1 Detecting Differences in Damped Sound Signals

A pilot test (1st experiment) was conducted to determine whether a sound signal is judged differently when the sound insulation and sound signals used as sources are different.

Nine untrained participants - five females and four males - were asked to listen to sound samples via headphone (Sennheiser HD 280 pro) and to judge the sound by answering pre-coded questions. The headphone was closed-back ensuring a 32 dB attenuation of external noise. The ear coupling of the headphone was circumaural and its frequency response is 8 Hz – 25,000 Hz.

The sound samples were played in different sequences to reduce the order effects.

The background noise level during the test was less than 25 dB(A) . The participants had self-reported normal hearing abilities and the median of age was 34. The participants were asked to select one of the following answers: 0 - *I do not hear a sound*; 1 - *I can hear a weak sound*; 2 - *I hardly hear a sound*; 3 - *Yes I can hear a sound but not easily*; 4 - *Yes I can hear a sound when concentrate on it*; 5 - *Yes I can hear a sound*; 6 - *Yes I can clearly hear a sound*. The test set-up and results are shown in Appendix VI.

The stimuli offered were the electronically filtered sound samples which were obtained using a filter function representing the sound insulation of interest. The filter function, i.e. the transfer function in the used software ArtemiS, was generated by modeling the *R*-values as the coefficients of the built transfer function.

The sound samples offered in this listening varied from R_w = 20 to 50 dB in steps of 10 dB and had a maximum sound insulation of 56 dB. The airborne sound insulation was calculated following the ISO 717-1 procedure (ISO717, 2013), and the insulation curves did not differ in their shapes. Source signals of white noise, pink noise, Eminem and Beethoven were used as described above. Due to the small sample size (n = 9), the non-parametric Wilcoxon-test, i.e. the Wilcoxon signed-rank test, was applied rather than the more commonly applied t-test. In contrast to the t-test, the Wilcoxon test does not require a normal distribution of the data set. A summary of the results is shown in Fig. 5-12, where a boxplot of the data response distribution is depicted.

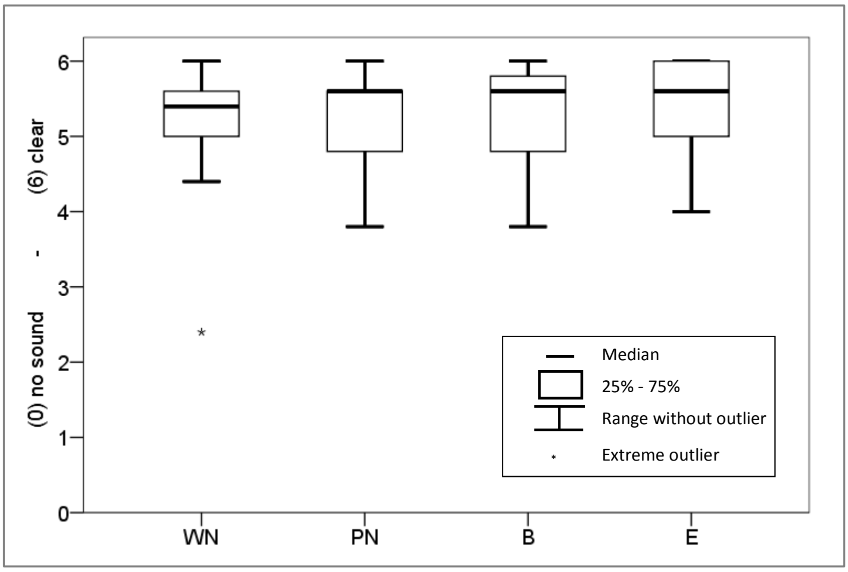


Figure 5-12: Overall results of the 1st experiment displayed as a boxplot of the response distribution for the data samples of white noise, pink noise, Beethoven, and Eminem.

The sound samples were generally judged to be similar; however, as shown in Fig. 5-13, the music signal is generally judged to be heard clearer than the broadband noise signal.

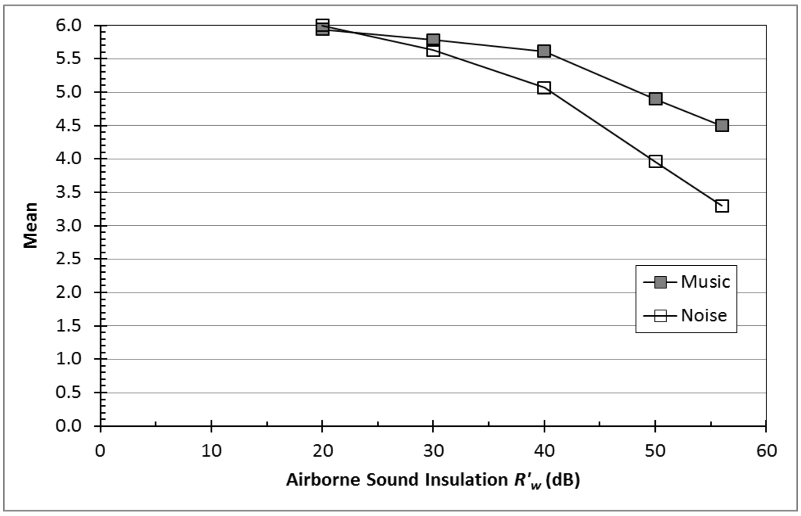


Figure 5-13: Mean of grouped and overall grouped response distribution from 1st experiment.

In Fig. 5-12, it is seen that pink noise is judged to be heard “clearer” than white noise, and “Eminem” is judged to be heard “slightly clearer” than “Beethoven”. In contrast, as shown in Fig. 5-13, the overall grouped response distribution of the two different sound samples is assessed differently.

Using a source level of 85 dB SPL, the airborne sound insulation of 56 dB was quoted for the broadband noise signals to have a median of 3.3 (“*Yes I can hear a sound but not easily”*) and for the music type signals with a median of 4.5 (something between: “(4)-*Yes I can hear a sound when concentrate on it” and “(5)-Yes I can hear a sound”*).

This is a strong indication that regardless of signal type, the sound insulation at 56 dB does not ensure privacy if the source level is above 85 dB. This experiment demonstrates that different sound samples were judged differently. It is found that music is judged to be heard more clearly than a broadband noise signal. This was seen for increasing R'_w-values. At low airborne sound insulation of approximately 20 and 30 dB, not much difference was observed. In this experiment, broadband noise was not as “audible” as music when the sound insulation rose beyond 40 dB. Comparison of the music type of the sound source revealed that Eminem was judged to be more audible in the presence of high sound insulation than Beethoven. Although the sample size in this experiment is small, conclusions regarding sound perception can still be drawn. It is concluded that music is heard more strongly than broadband noise, in line with everyday experience.

These findings apply to the spectral shape of the sound reduction index as shown in Appendix V, b) where no frequency dip is introduced in the frequency depending filter coefficients.

5.2.2 Detecting Differences in Sound Signals with equal SPL

Following the pilot study (1st experiment), the aim of this listening test (2nd experiment) was to find evidence that the loudness of different types of sound signal is judged differently depending on the type of signal. In this test, one hundred untrained participants (92 male, 8 female) were asked to listen to sound samples via loudspeakers and to judge their loudness. The participants had self-reported normal hearing abilities and the median of age was 46. The different presentation method of the acoustical stimuli was needed because the test was conducted for all participants simultaneously. The acoustic stimuli were played in different sequences for the participants to decrease the order effects. The stimuli offered were the electronically filtered sound samples which were obtained using a filter function representing the sound insulation of interest.

The experiment involved 5 different sounds: WN, PN, E, B, and PS with three different sound levels (i.e. 40, 50, and 60 dB SPL) and was designed such that every sound was compared against all others. The participants were therefore presented two sound signals at the same sound pressure level sequentially. The duration of each sound sample was 5 s. Each sound pair was played in a row, and the participant was asked to decide whether the latter sound was louder or quieter than the former and was asked to rate the sound from -5 to +5, where -5 indicates “much quieter”, zero: “equally loud” and +5: “much louder”.

In contrast to the pilot study the participants were asked to decide which sound appears to be “louder” instead of “clearer”. This change was due to the purpose of the experiment to find evidence that different sound samples having same sound pressure level appear to be heard differently in a subjective aspect. Therefore three different sound levels were compared instead of different filter functions as was done in the first experiment.

In the experiment, all 5 sounds were joined in 12 pair comparisons (such as WN: WN vs. PN, WN vs. E, WN vs. B and WN vs. PS; at 40 dB, 50 dB to 60 dB). A sound sample could accumulate at most -60 points over 12 pair comparisons. By extension, for 100 participants, a sound sample could reach at most -6,000 points over a total of 1,200 pair comparisons, representing -5 points per pair comparison. The test set-up and detailed results are shown in Appendix VII.

The 5 sounds (WN, PN, E, B, and PS) reached the following points:

- WN reached -1,066 points in all 1,200 pair comparisons (Ø: -0.89).
- PS reached -433 points in all 1,200 pair comparisons (Ø: -0.36).
- PN reached -254 points in all 1,200 pair comparisons (Ø: -0.21).
- B reached +543 points in all 1,200 pair comparisons (Ø: +0.45).
- E reached +1,210 points in all 1,200 pair comparisons (Ø: +1.01).

(Note: score offset, i.e. plus and minus points sum up sometimes.)

The 5 sound variables calculated in accordance with the above strategy (point averages from 12 pair comparisons) were compared using both the t-test for related samples and the Wilcoxon test to determine whether the mean differences between the noises (whether softer or louder) were significant (i.e., whether the differences could be generalized and applied to a larger population). The difference between the two variables was tested in advance using the Kolmogorov-Smirnov test for normality. If the difference was based on a normal distribution, the t-test could be applied to related samples; otherwise, the non-parametric Wilcoxon test was applied.

The analyses showed that the t- and Wilcoxon tests produced the same result with regard to the significance of the differences between the sounds. It was observed that white noise (WN) received the most (-) points, making it the quietest perceived sound sample of all pairs and all subjects compared. Eminem (E), in contrast, received the most (+) points, making it the loudest perceived sound sample.

To summarize the results it was obtained that white noise (WN) was judged being the quietest perceived sound sample about the comparisons of all couple and all subjects. Eminem (E) on the other hand was judged being the loudest perceived sound sample about the comparisons of all couple and all subjects.

These analyses show that the significance ($p < 0.05$) of the differences between white noise (WN) sounds is highly significantly ($p < 0.001$); it is judged as “quieter” than the other sound samples. A summary of the results is shown in Fig. 5-14, where the boxplot of the response distribution of the data samples is depicted.

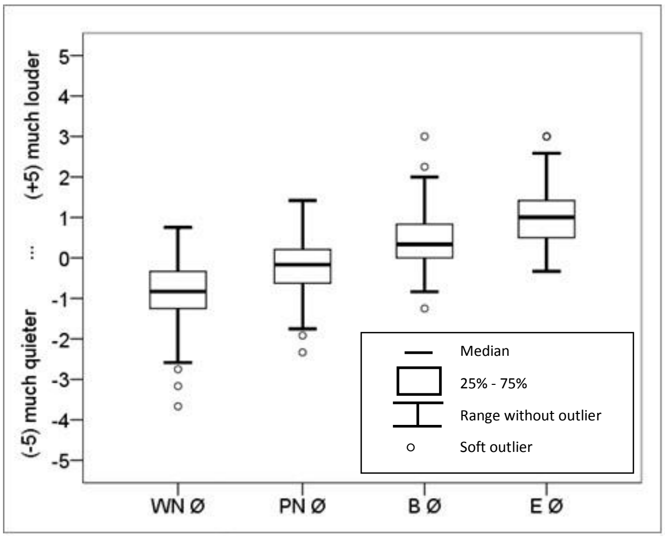


Figure 5-14: Results of the 2nd experiment displayed as boxplot of the response distribution data comparing all results.

The interpretation of the results in Fig. 5-14 is that a lower value is correlated with a lower perception of a particular sound compared to the others presented. White noise was overall judged to be the quietest, while Eminem was the loudest. This confirms the results of the first pilot survey (see Fig. 5-13).

5.2.3 Detecting Differences in Damped Sound Signals with equal *R*-values

The goal of the third listening test (3rd experiment) was to find evidence that the perceived sound level after transmission differs with frequency, depending on the nature of airborne sound insulation (all types have the same R_w-value).

The equipment used and the procedure of this test was the same as for the first test. The experiment involved 5 different sounds: WN, PN, E, B, and PS, as for the second test. All source signals had a sound pressure level of 85 dB SPL and a duration of 15 s.

Eleven untrained participants (8 male, 3 female) were asked to listen to sound samples through headphones (Sennheiser HD 280 pro) and to judge the sound by answering pre-coded questions. All participants reported normal hearing and the median of age of the participants was 42. Five types of airborne sound insulation (i.e., filter types), labelled "*I* to *V*", were tested. Type "*V*" was an extended reference curve, which, according to ISO 717-1, is thought to be a reference for a sound reduction index of 50 dB (R_w = 50 (-2; -6) dB).

The sound reduction index R_w of the filter types is depicted over frequency in Fig. 5-15.

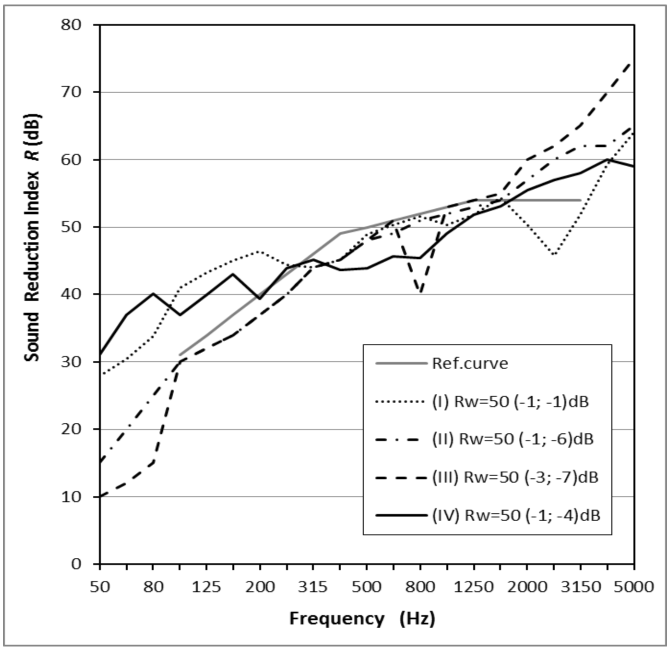


Figure 5-15: Sound reduction index R_w over frequency for the filter types (“*I – IV*”).

The participants were asked to listen to the sounds and to rank them from quietest to loudest. They could listen to the sound samples as many times as they wanted.

The participants were asked to select one of the following answers: 0 - quietest; 1 - quiet; 2 - equal; 3 – loud; 4 - loudest.

The listening test was conducted such that a sound sample (e.g., Beethoven) was played to the subjects through the different filters (“*I*” to “*V*”). The test set-up, data sheet and detailed results are shown in Appendix VIII. The participants then ranked the variants of the sound sample from loudest to quietest. All sounds per filter were averaged and combined for data evaluation. This was done to compare the two filters rather than the sound signal. An evaluation of the data collected after the listening test was performed.

The collected data are summarized and described quantitatively in Fig. 5-16.

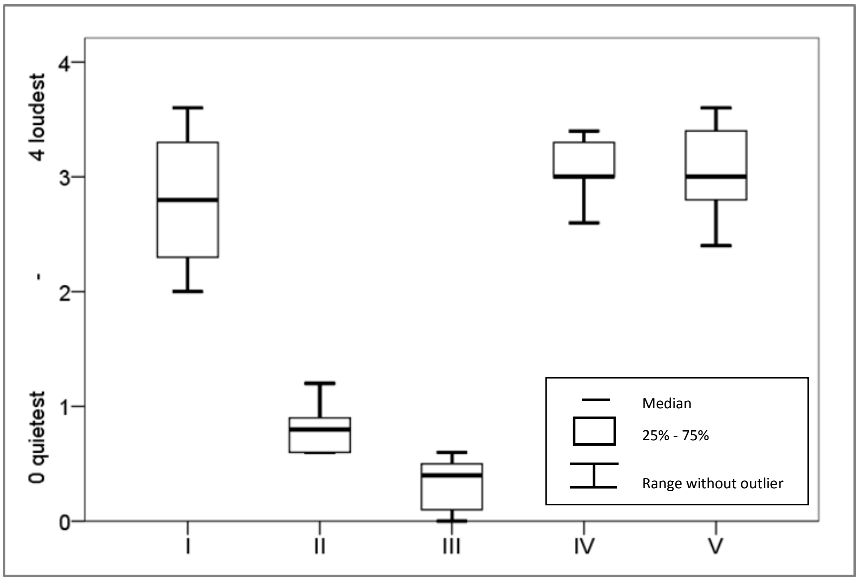


Figure 5-16: Results of the third experiment displayed as boxplot of the response distribution for the data samples, *type* "*I* to *V*". Note, the type *"V"* is the reference curve according to ISO 717-1.

Considering the sample size (n = 11), the non-parametric Wilcoxon test was applied rather than the t-test. It can be seen in Fig. 5-16 that type "*III*" is judged to be quieter than all other types. The filter type "*III*" differs significantly ($p < 0.05$) from the filters "*I*, *II*, *IV*", and "*V*", respectively. There is no significant difference among the filters *"I*, *IV"*, and "*V"* (i.e., these filters are recognised to be the loudest). They are, however, significantly different from filters "*II*" and "*III*".

This result is a strong indication that airborne sound insulation is judged differently depending on the frequency-dependent R_w-value. This is in line with previous findings (Neubauer and Kang, 2011b).

It is noted that comparing the spectra of the respective sound insulation and the resulting *C*-values it is indicated that case "*III*" has little sound insulation at low frequencies and a dip at 800 Hz whereas case *"I"* has high sound insulation at low frequencies and a dip at 2.5k Hz. This could be an indication that low frequencies do not contribute significantly to the subjective assessment of a sound insulation. These observations thus invite further discussion on applicability of adaptation terms according to ISO 717-1 to other noise sources.

However, the present work does not cover the suitability of different representative normalized spectrum for ascertaining the sound insulation performance towards different noise spectra. This topic refers to the relevant literature, e. g. (Fothergill,1980; Taibo and Glasserman de Dayan, 1983; Kropp et al. 1994; Lang, 1997; Fausti et al. 1999; Smith et al. 2003, 2007; Park et al., 2008; Park and Bradley, 2009; Scholl et al., 2011; Garg et al., 2013; Ljunggren et al., 2014; Hongisto, 2015) and is a task for further investigations in the field of subjective assessment tests.

5.3 Model Implementation

The filtered sound signal (i.e., the level of interest) has been reported to be a measure of perception, suggesting that any dips in frequency-dependent airborne sound insulation should be included in the model. This will be shown explicitly for single frequency dips in frequency-dependent airborne sound insulation. The frequency-dependent value enables characterization of the frequency range of a dip.

The overall performance of the model is then demonstrated by a single value representing the magnitude of deviation from the ideal value. This single value therefore enables characterization of an *R*-value as “reliable” or “not reliable”. This means that if the airborne sound insulation is “real”, it is likely that the perceived sound is subjectively assessed to be equivalent to the calculated sound. If the airborne sound insulation is “not reliable”, then the airborne sound insulation is considered to be subjectively different from the expected airborne sound insulation.

5.3.1 Frequency Dependence and Single Numerical Values

To examine the effect of a frequency-dependent dip in the airborne sound insulation curve, a frequency dip was introduced in a hypothetical sound insulation curve.

First, an idealized imaginary airborne sound insulation was investigated to demonstrate the theoretical behaviour of the function. A comparison was performed between sound insulation curves with and without the frequency dip.

Then, the performance of airborne sound insulation assessed at a test site was compared with the theoretical computed airborne sound insulation using standard theory.

Finally, the results of an in situ examination of two real airborne sound insulations, each with a pronounced dip in the sound insulation curve (biased value), were compared with calculated standard values (unbiased value).

5.3.1.1 Calculated Idealized Airborne Sound Insulation

A calculated idealized airborne sound insulation of 40 dB with a 6 dB frequency single dip at each 1/3rd octave band frequency from 160 Hz to 5,000 Hz was considered. The source signal was pink noise at a sound pressure level of 85 dB. The depth of the dip with 6 dB was chosen in accordance with the ISO standard 16283-1 (2014) for the default procedures as a minimum level to get a level contribution. Figure 5-17 shows an exemplary calculated airborne sound insulation of 40 dB, with a 6 dB dip at a frequency of 500 Hz.

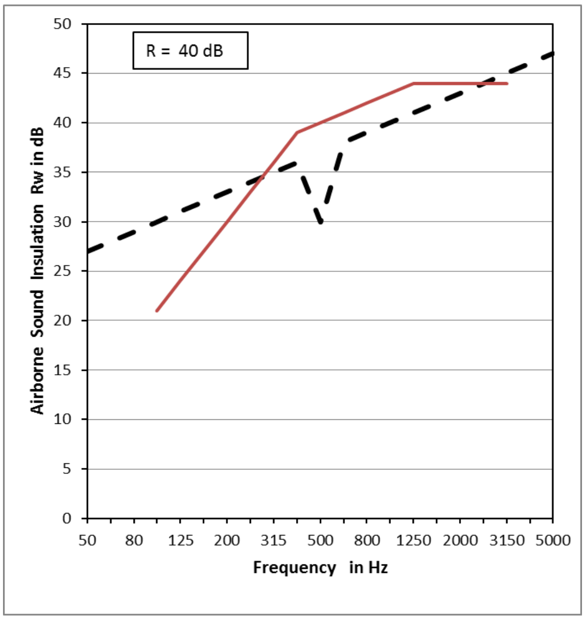


Figure 5-17: Airborne sound insulation with a dip of 6 dB at 500 Hz. The solid line is the reference curve given in EN ISO 717-1. Example R_w = 40 dB.

The calculated differences in frequency-dependent normalized loudness level ($L_{nor(f)}$) according to Eq. (4-6) are shown in Fig. 5-18. The effect of a 6 dB dip is evident.

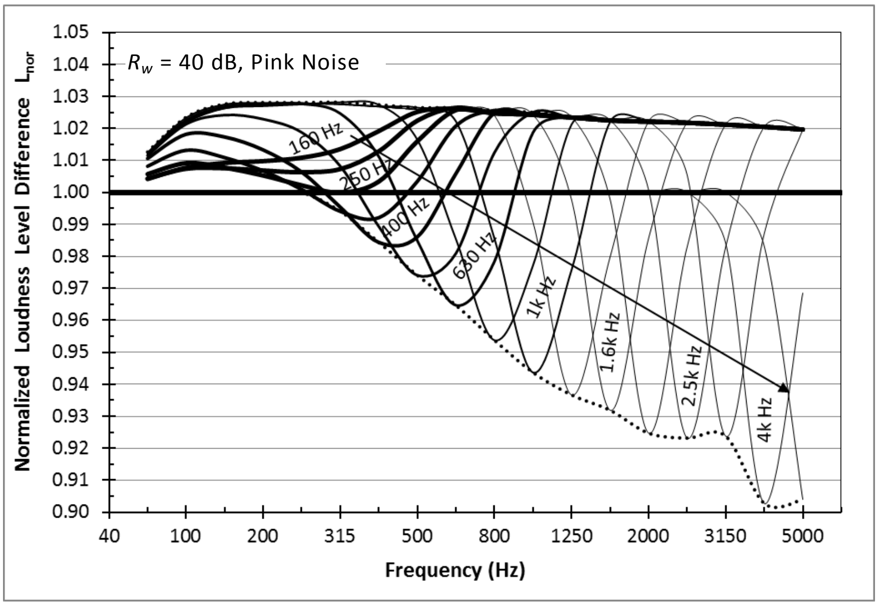


Figure 5-18: Normalized loudness level difference over frequency, R_w = 40 dB with a single dip of 6 dB at each 1/3rd octave band frequency from 160 Hz up to 5,000 Hz. Source signal pink noise having a SPL of 85 dB. Each solid line shows L_{nor} with a dip at one frequency and the dotted line shows the envelope.

The influence of the single frequency dip to the normalized loudness level difference was at least one third-octave band below and above the dip in the frequency range. This means that the dip enlarged the influence of a single frequency dip on the difference in normalized loudness level. The envelope depicted in Fig. 5-18 (dotted line) reveals that with increasing frequency, the minimum value of the normalized loudness level difference decreased. This means that the frequency dip reduced the airborne sound insulation. The maximum value (L_{nor} > 1) increases steeply for low frequencies up to approximately 160 Hz. From 160 Hz up to 5k Hz, a nearly constant value was observed. The calculated mean and standard deviation for the linear range (160 Hz – 5k Hz) is L_{nor} = 1.024 $\pm$ 0.003.

It was observed from the envelope that for minimum values, low frequencies are constant up to 250 Hz. Above this frequency, the frequency values decreased linearly to approximately 2.5k Hz. Above that frequency, some deviation was observed.

This is illustrated in Fig. 5-19, where the min- and max-values are depicted.

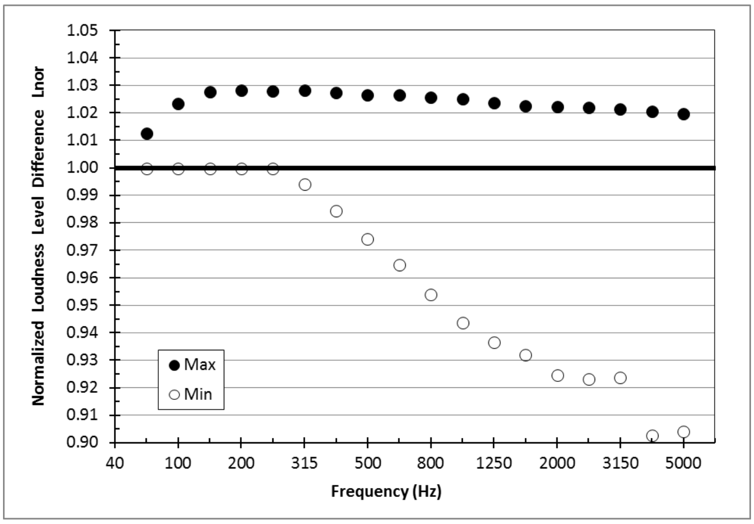


Figure 5-19: Min-, max-values taken from Fig. 5-18.

Overall, it is determined empirically that regarding the difference in normalized loudness level for all investigated sound signals, the filtered or processed sound is perceived to be louder when a frequency dip is introduced in the airborne sound insulation. Although the single value of the airborne sound insulation was not altered much, the dip is thought to cause a sensation that results in the perception of increased loudness. Introducing weighting (w), as defined in Eq. (4-8), yields the weighted normalized loudness level difference ($L_{nor,w(f)}$), as defined in Eq. (4-10). As an example, the results obtained using again pink noise as a source signal are illustrated in Fig. 5-20.

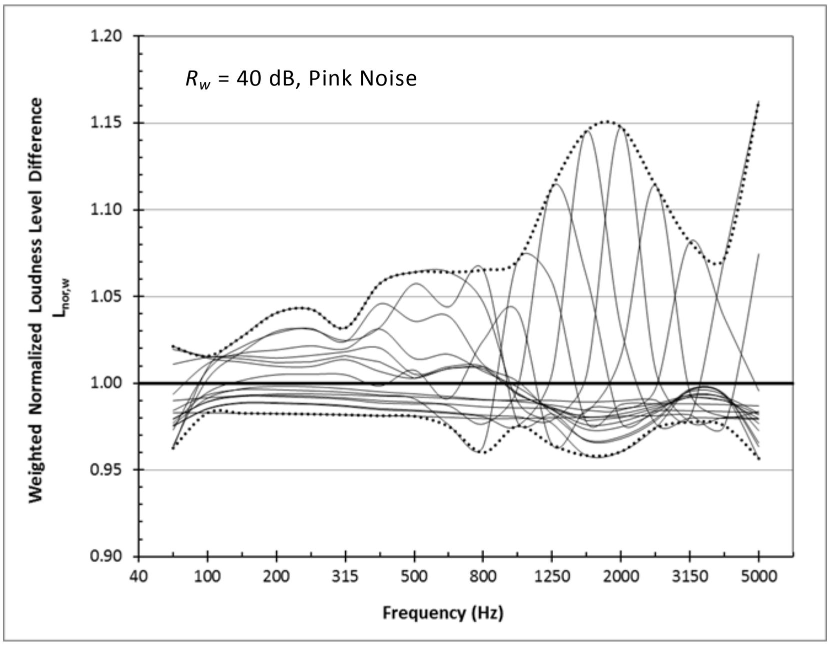


Figure 5-20: Weighted normalized loudness level difference over frequency, R_w = 40 dB with a single dip of 6 dB at each 1/3rd octave band frequency from 160 Hz up to 5,000 Hz. Source signal pink noise having a SPL of 85 dB. Each solid line shows $L_{nor,w}$ with a dip at one frequency and the dotted line indicates the envelope.

The weighted normalized loudness level difference ($L_{nor,w(f)}$) shows the event of a frequency dip, as does the normalized loudness level difference (L_{nor}). A reversed picture was drawn comparing the normalized loudness level difference and the weighted normalized level difference. This is an indication that the specific fluctuation strength significantly (Fls') influenced the weighted normalized loudness level difference ($L_{nor,w(f)}$).

5.3.1.2 Measured Airborne Sound Insulation in a Test-Site

To investigate a real construction without the influence of a flanking construction, measurements taken in a laboratory were used. The values of the measured airborne sound insulation were taken from a database provided by the manufacturer ("Bundesverband Kalksandsteinindustrie e.V.") for sand-lime bricks of different thicknesses. The detailed parameters are provided in Appendix IX.

In Tab. 5-4 the measured and calculated R_w-values, the mass per area, the thickness of the sand-lime brick, and the differences between measured and calculated R_w-values are shown.

Table 5-4: Calculated and measured airborne sound insulation of sand-lime brick.

t (mm)	70	115	150	175	240	300
m' (kg/m²)	130	180	285	341	475	614
R_w (C; C_{tr}) (dB)	43 (-1; -5)	46 (-1; -4)	54 (-1; -5)	56 (-1; -5)	60 (-1; -5)	63 (-2; -5)
$R_{w,calc}$ (C; C_{tr}) (dB)	42 (-1; -3)	45 (-0; -3)	51 (0; -4)	54 (-1, -5)	59 (-1, -5)	63 (-1; -6)
ΔR (dB)	1	1	3	2	1	0

The corresponding frequency-dependent values are presented in Appendix IX, where the measured and calculated values are also depicted graphically.

The calculation of the respective airborne sound insulation was done using the software INSUL 8.0. In App. IX, b), R_w-values over the frequency of the sand-lime brick are depicted for thicknesses of t = 70/115/150/175/240/300 mm. The computed frequency-dependent airborne sound insulation above a frequency of 200 Hz matches the measured values except at the thickness of 70 mm. In addition, some deviations were observed below 200 Hz.

It was noted that the calculated results for thicker (i.e., heavier) bricks better matched their measured values. In Fig. 5-21 the “worst” and “best” results are shown for comparison. We observed that constructions with a thickness of 70 mm yielded good results above a frequency of 315 Hz, whereas constructions with a thickness of 240 mm yielded good results even for low frequencies. The full results are presented in the appendix.

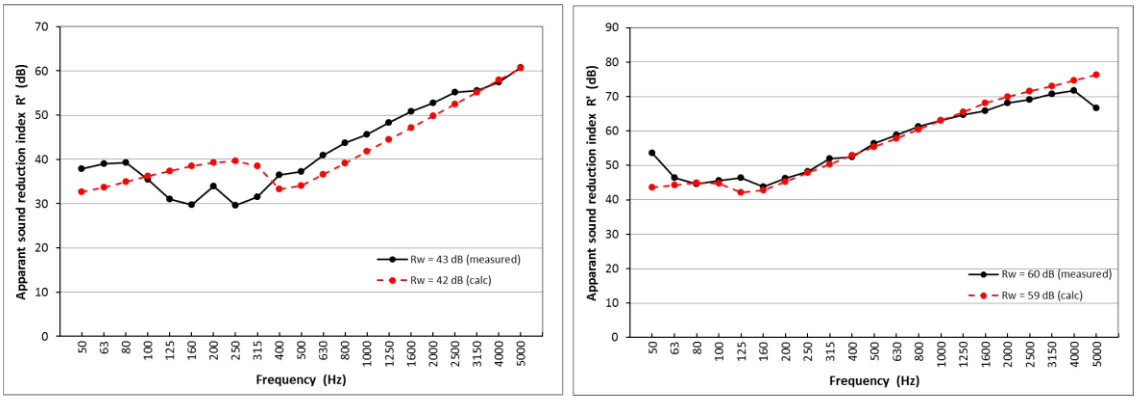


Figure 5-21: Calculated and measured airborne sound insulation for sand-lime brick. The left panel shows results for a sand-lime brick of 70 mm and the right panel shows results for a thickness of 240 mm.

Table 5-5: Calculated weighted normalized loudness level difference ($L_{nor,w}$).

Thickness Mm	Weighted normalized loudness level difference ($L_{nor,w}$) for different thicknesses and different sound signals				
	WN	PN	E	B	PS
70	1.060	1.078	1.041	0.987	1.079
115	0.901	0.964	1.005	0.996	1.069
150	0.929	0.940	0.987	0.983	1.009
175	0.925	0.912	0.977	0.998	0.970
240	0.897	***0.862***	0.990	1.004	0.975
300	1.033	0.905	1.038	1.010	***1.081***
Mean	0.957	0.943	1.006	0.996	1.030
Standard deviation	0.071	0.074	0.027	0.010	0.052

The bold numbers in Tab. 5-5 are the minimum and maximum values measured. A minimum value (0.862) was observed using pink noise insulated by a construction of sand-lime brick of thickness 240 mm, while a maximum value (1.081) was observed for the sound sample “party sound” insulated by a construction of sand-lime brick of thickness 300 mm. It is seen in Tab. 5-5 that the “party sound” sample, followed by the music sample “Eminem”, yielded the highest mean values. The broadband noise samples (pink and white noise) yielded the smallest values.

In Figs. 5-22 and 5-23 all results are depicted graphically for comparison. Figure 5-22 depicts results for the normalized loudness level difference (L_{nor}) for different sound samples. Analysing Eq. (4-7) it is clear that a value greater than 1 indicates that the measured airborne sound insulation (R_w) performs better than calculation.

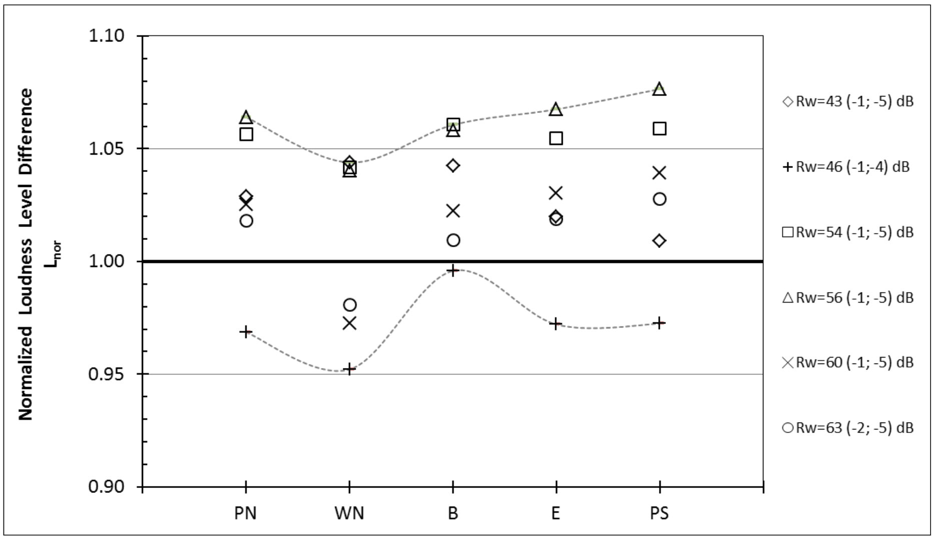


Figure 5-22: Normalized loudness level difference (L_{nor}) for different sound samples calculated for a single wall construction of sand-lime brick of thickness ranging from 70 mm to 300 mm and calculated sound reduction index R_w (C; C_{tr}). The upper and lower dotted grey line indicates the region for the individual results.

Figure 5-23 shows the weighted normalized loudness level difference ($L_{nor,w}$) for different sound samples. Analysing Eq. (4-11) reveals that results greater than 1 indicate a tendency that theoretical values in comparison to measurements are overestimated.

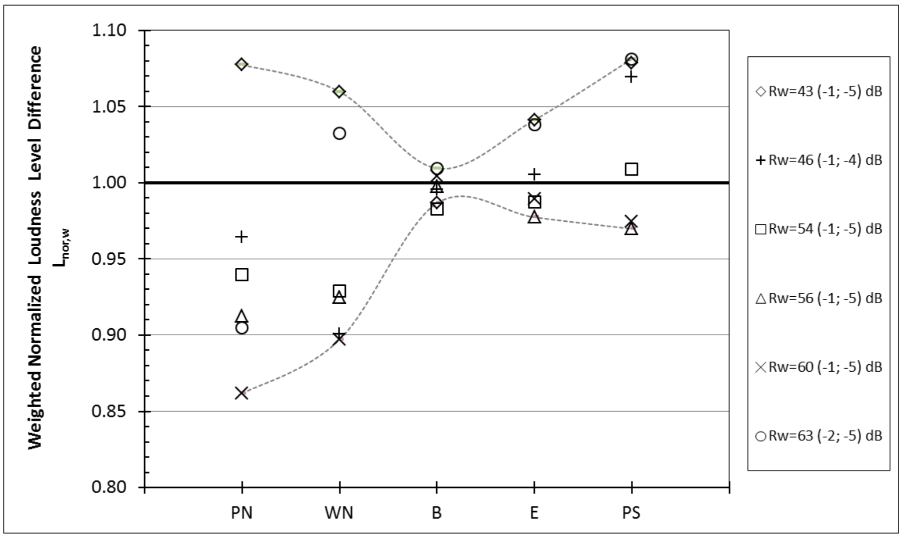


Figure 5-23: Weighted normalized loudness level difference ($L_{nor,w}$) for different sound samples calculated for a single wall construction of sand-lime brick of thickness ranging from 70 mm to 300 mm and calculated sound reduction index R_w (C; C_{tr}). The upper and lower dotted grey line indicates the region for the individual results.

In Fig. 5-23 it is clear that the music sound sample “Beethoven” yielded the smallest values, whereas the broadband noise signal “pink noise” showed large variation in response. This is also indicated by the calculated standard deviation of the mean for pink noise. Pink noise yielded results as shown in Tab. 5-5: $\pm$ 0.074 whereas Beethoven yielded the smallest standard deviation: $\pm$ 0.010.

This section showed clearly that different sounds yield different weighted normalized loudness level differences indicating a large scattering of measured and predicted results.

5.3.1.3 Measured Airborne Sound Insulation In-Situ

In this section, a two-fold measurement was conducted to verify the proposed model. First, the airborne sound insulation of three partitions was measured in situ due to resident complaints. In a second stage, measurements and ratings of the airborne sound insulation between two rooms were carried out after each material improvement step. This documented the effectiveness of each successive improvement in airborne sound insulation. The used instruments to carry out the measurements are listed in Appendix X.

5.3.1.3.1 Three Partition Measurements

Two samples were lightweight constructions, and one sample was a heavyweight construction. Measurements were taken according to ISO 16283-1. The frequency-dependent airborne sound insulation was converted to a single number rating using the Standard ISO 717-1. Briefly, this procedure uses a reference curve shifted against the frequency-dependent values. Figure 5-24 shows the measured frequency-dependent airborne sound insulation and the shifted reference curve based on ISO 717-1. In the left panel, the airborne sound insulation of a lightweight ceiling (i.e., a wood ceiling) having R'_w =36 dB is shown.

In the middle and right panels of Fig. 5-24 a gypsum board wall having R'_w =51 dB and a masonry wall having R'_w =54 dB, respectively, are shown.

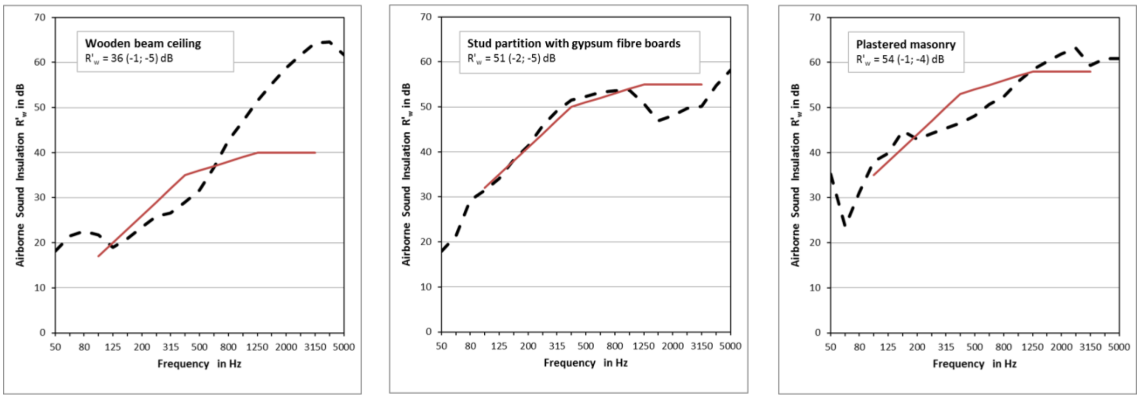


Figure 5-24: Measured airborne sound insulations. The solid line is the reference curve given in ISO 717-1.

As an example Fig. 5-25, shows the measured sound pressure level and the corresponding computed loudness level for different sound signals after transmission through a wall having R'_w = 54 dB.

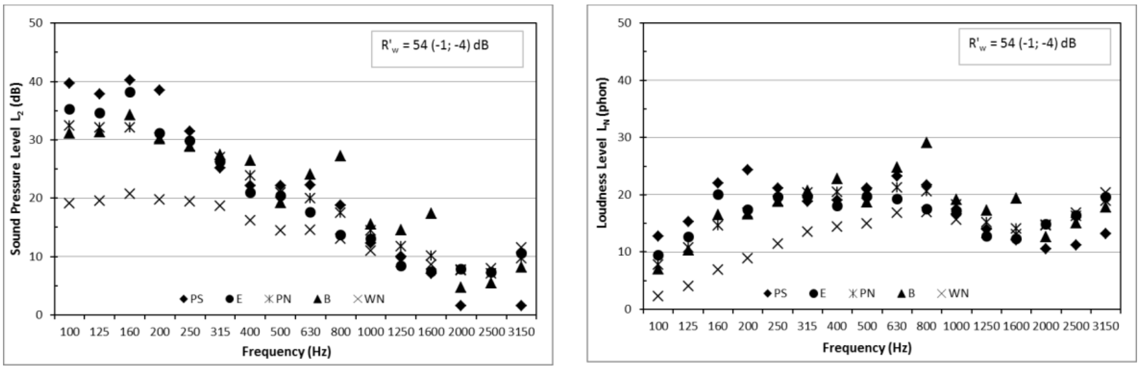


Figure 5-25: Measured sound pressure level (L_2) and calculated loudness level (L_N).

The method used to obtain calculated airborne sound insulation values is provided in the European Standard EN12354-1 (EN12354-1, 2000).

The results of the calculation of airborne sound insulation for the investigated partitions are compared with the measured values in Tab. 5-6.

Table 5-6: Calculated and measured airborne sound insulation.

Measured (ISO 16283-1)	Calculated (EN 12354-1)	Construction
R'_w = 36 (-1; -5) dB	R'_w = 36 (-1; -5) dB	Wooden beam ceiling
R'_w = 51 (-2; -5) dB	R'_w = 55 (-3; -10) dB	Gypsum fibre board wall
R'_w = 54 (-1; -4) dB	R'_w = 54 (-2; -6) dB	Masonry wall plastered

Figure 5-26 shows the computed normalized loudness level differences (L_{nor}) for the three investigated constructions with different airborne sound insulation properties.

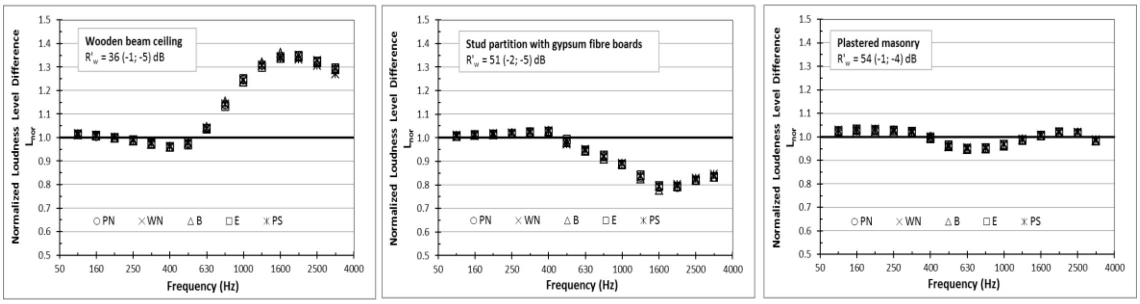


Figure 5-26: Normalized loudness level difference over frequency according to Eq. (4-6).

Applying the weighting (w) according to Eq. (4-8) as depicted below in Fig. 5-27 yields the weighted normalized loudness level difference ($L_{nor,w}$) which is shown as a function of frequency in Fig. 5-28.

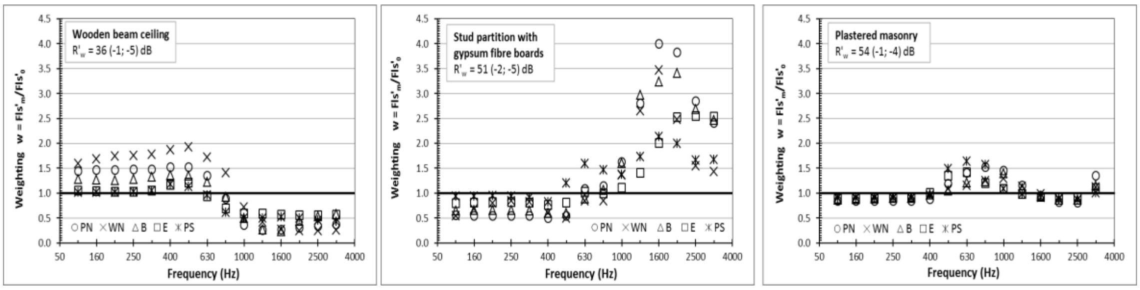


Figure 5-27: Calculated weighting over frequency according to Eq. (4-8).

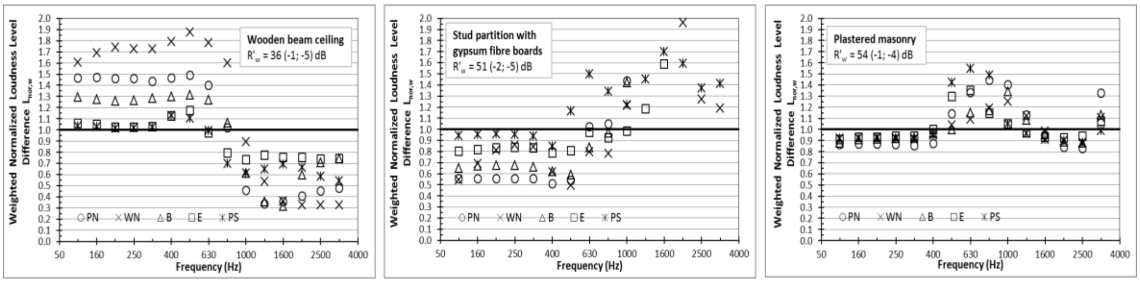


Figure 5-28: Frequency dependent weighted normalized loudness level difference Eq. (4-10).

The calculation of the normalized loudness level difference (L_{nor}) using Eq. (4-7), weighting (w) using Eq. (4-9), yields a single number quantity for the weighted normalized loudness level difference ($L_{nor,w}$) according to Eq. (4-11). The results are depicted in Tab. 5-7.

Table 5-7: Single number values for the investigated sound insulations and sound samples

Sound Sample	R'_w = 36 (-1; -5) dB			R'_w = 51 (-2; -5) dB			R'_w = 54 (-1; -4) dB		
	L_{nor}	W	$\boldsymbol{L_{nor,w}}$	L_{nor}	w	$\boldsymbol{L_{nor,w}}$	L_{nor}	w	$\boldsymbol{L_{nor,w}}$
PN	1.13	1.11	**1.25**	1.03	0.83	**0.85**	0.99	0.99	**0.98**
WN	1.18	1.21	**1.43**	1.07	1.06	**1.13**	0.98	1.01	**0.99**
B	1.11	0.92	**1.02**	1.03	1.13	**1.16**	0.99	1.01	**1.00**
E	1.09	0.96	**1.05**	0.99	1.06	**1.05**	1.01	0.99	**1.00**
PS	1.07	0.97	**1.04**	1.00	1.00	**1.00**	1.00	0.95	**0.95**

The single number values (i.e., the normalized loudness level differences), the weightings and the weighted normalized loudness level differences, as reported in Tab. 5-7, are shown in Fig. 5-29.

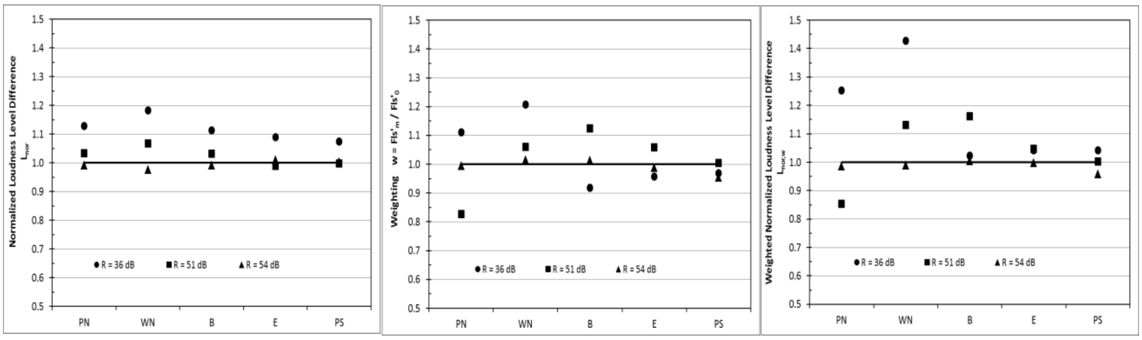


Figure 5-29: Calculated single values according to Eq. (4-7), (4-9), and (4-11), respectively.

The results presented in this section shows that a simple level difference as specified by the loudness level difference (L_{nor}) fictionally implies that, when $L_{nor(f)}$ > 1 a measured or unbiased sound reduction index (R_w) performs better than the calculated R-value indicates.

However, investigating in detail the weighting ($w_{(f)}$) it becomes clear that this interpretation can be false. This is seen by analysing the results presented in Fig. 5-26.

Consequently, it is concluded that a sound level difference (ΔL) does not well reflect the effect of the sound source spectrum on the airborne sound insulation. Therefore, a level difference is considered not being a well reliable descriptor for judging airborne sound insulation relating to different sound samples.

5.3.1.3.2 Successive Enhanced R'_w-value

This part of the study focused on a situation in which a dividing floor between two vertically situated rooms in a two-family house of solid construction located in southern Germany was reported to provide less airborne sound insulation than expected. The respective rooms under investigation were the bedroom on the ground floor and the living room on the upper floor. The building section and the floor plans are shown Fig. 5-30, depicting the room configuration and the direction of measurement.

The external wall, which was made of brick, had a low U-value (the overall heat transfer coefficient), which ensured fulfilling the requirements for thermal protection. The brick had a density of 650 kg/m³ and the density of the internal walls were 800 kg/m³.

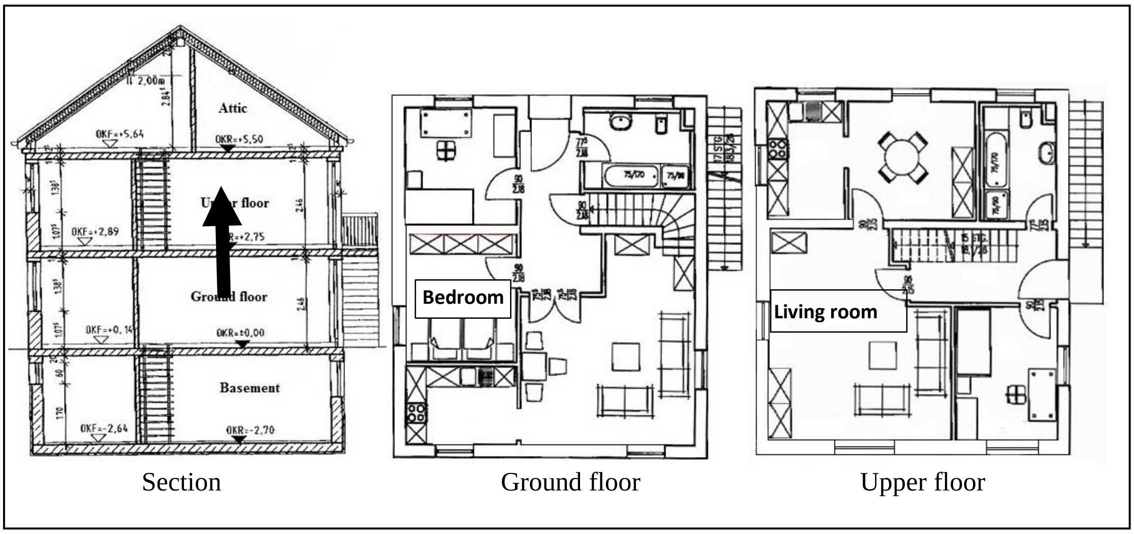


Figure 5-30: Section view of the building and floor plans. The direction of measurement is indicated by an arrow. The receiving room was the bedroom on the ground floor, and the source room was the living room on the upper floor.

As seen in Fig. 5-30, the bedroom on the ground floor has one external wall with a thickness of 365 mm, one internal wall with a thickness of 240 mm and two internal walls with thicknesses of 115 mm, and 125 mm, respectively. The living room on the upper floor has two external walls with thicknesses of 365 mm, one internal wall with a thickness of 240 mm and one internal wall with a thickness of 115 mm. All of the masonry walls were plastered.

The sound insulation of the separating floor was first tested in its original state, yielding a measurement of *in situ* airborne sound insulation. It has been shown that the sound power transmitted into a receiving room can be represented by the sum of several components from different elements (e.g., walls, floor, ceiling etc.), thus, the influence of the resulting sound insulation by different treatments was investigated on these flanking constructions (i.e., on the walls).

The steps taken are described in cases 2 to 4. After each step, the airborne sound insulation was measured again so that a direct comparison of the results was possible.

The construction being tested was a concrete floor base with a thickness of 180 mm and a floating floor on top. The floating floor was built of cement screed with a thickness of 55 mm, which was laid over the structural floor but remained separated by a layer of resilient material. The floor was covered with parquet. The pre-treatment airborne sound insulation refers to the initial situation without any changes to the flanking walls and is referred to as case 1. The changes to the flanking constructions are described in the respective cases 2 - 4.

Case 1: In the source room, there were three plastered masonry walls and one framed plasterboard wall. There were two external masonry walls with a thickness of 365 mm, and one internal masonry wall with a thickness of 240 mm. The plasterboard wall had a thickness of

125 mm. The volume density of the external masonry walls was 650 kg/m³, and that of the internal walls was 800 kg/m³. The receiving room walls were all masonry. There was one external wall with a thickness of 365 mm, one internal wall with a thickness of 240 mm and two internal walls with thicknesses of 115 mm and 240 mm. All of the masonry walls were plastered. The measured reverberation time in the receiving room was 0.48 s, and the room volume was 29.3 m³.

Case 2: An additional independent free-standing panel consisting of 2 layers of plasterboard with staggered joints and mineral wool in the cavity was built on the inner sides of the external and one internal wall in the source room to reduce flanking transmission.

Case 3: The same as Case 2, with additional independent panels at the two external walls in the receiving room.

Case 4: The same as Case 3, with the addition of two more independent panels (i.e., all four walls in the receiving room had independent panels).

It was also of interest to learn how transmitted sound is affected by speech as a source signal because overhearing neighbours' conversations was a specific complaint. For this reason, the speech level was measured. The measured frequency-dependent speech level of a male is depicted in Tab. 5-8.

Table 5-8: Sound pressure level (SPL) used as the source level to calculate the receiving level.

Speech level L_{speech} in dB SPL (L_{eq} = *75 dB SPL*)																				
Frequency in Hz																				
50	63	80	100	125	160	200	250	315	400	500	630	800	1k	1.25k	1.6k	2k	2.5k	3.15k	4k	5k
28.5	30.0	32.3	32.3	46.3	66.6	68.7	63.7	63.5	65.2	65.5	65.4	57.7	58.5	60.8	58.9	55.1	54.3	47.1	41.2	42.4

It is seen that the sound pressure level varies from 50 Hz to 160 Hz in a nearly step-wise manner. This indicates that less sound energy is generated below a frequency of 160 Hz. From 100 Hz to 160 Hz, the sound pressure level rises very steep, and beyond the maximum sound pressure level of 200 Hz, it begins to fall off continuously (see Fig. 5-31).

In addition, the background noise level in the receiving room was measured to assess whether the background noise level influences transmitted sound in the receiving room. The standard ISO 16283-1 describes how to apply a correction to the signal level for background noise. The measured frequency-dependent background noise level is shown in Tab. 5-9.

Table 5-9: Sound pressure level (SPL) of the background noise level.

Background noise level $L_{eq,BGN}$ in dB SPL ($L_{eq,BGN}$ = *29.7 dB SPL*)																				
Frequency in Hz																				
50	63	80	100	125	160	200	250	315	400	500	630	800	1k	1.25k	1.6k	2k	2.5k	3.15k	4k	5k
26.6	19.0	19.9	17.8	17.2	11.1	13.2	17.5	22.7	15.7	11.0	8.7	10.4	12.0	12.7	12.6	13.3	12.1	10.5	10.0	11.2

Figure 5-31 compares the measured speech level and the measured background noise level and plots the hearing threshold against frequency. The absolute threshold of hearing according to ISO 226 is depicted. Background noise exists for frequencies more than 160 Hz above the threshold, which means the background noise level is audible, although the overall sound pressure level of the background noise is very low. The unweighted measured sound pressure level was $L_{eq,Speech}$ = 75 dB, and the unweighted background noise level was $L_{eq,\ BGN}$ = 29.7 dB. It is evident that the background noise level is reduced with increasing frequency. This is a general characteristic of background noises measured in the context of building acoustics.

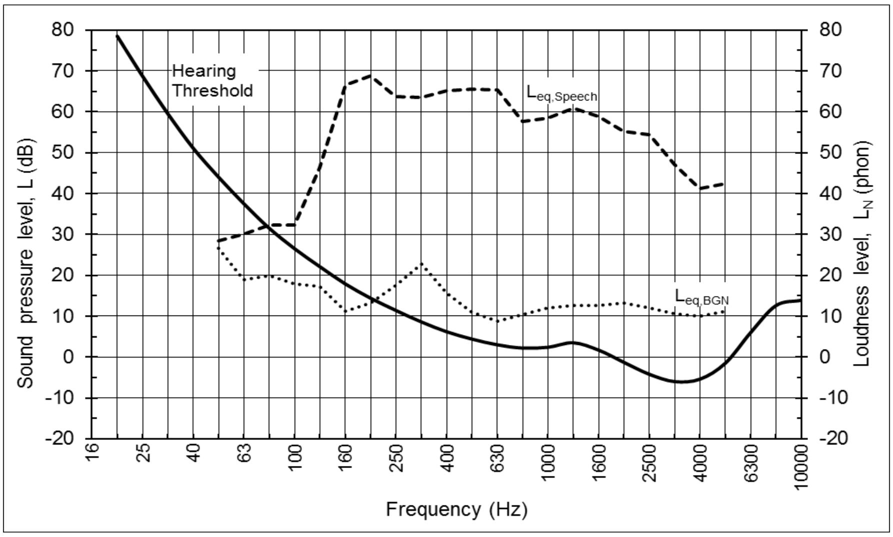


Figure 5-31: Measured sound pressure level $L_{eq,Speech}$ = 75 dB and background noise level $L_{eq,\ BGN}$ = 29.7 dB SPL compared to the absolute threshold of hearing according to ISO 226.

The measurement of airborne sound insulation *in situ* followed the international standard ISO 16823-1. This standard specifies a procedure to determine the effectiveness of airborne sound insulation between two rooms in a building using sound pressure level measurements. It was intended to be used for room volumes up to 250 m³.

The sound spectra were measured in one-third-octave bands over a frequency range of 50 Hz to 5,000 Hz. The procedure requires that one room is chosen as the source room containing the loudspeaker and another room is chosen as the receiving room. An omnidirectional loudspeaker (Dodecahedron) was used as a sound source with pink noise as a source signal.

The average sound pressure levels in the source and receiving rooms were measured simultaneously at several microphone positions. The measurement equipment was a two channel real time analyser. The measurement set-up is listed in Appendix X.

The measurements were performed according to the procedure described and specified in section 2.4.

Based on the original design defined in case 1 with an apparent weighted sound reduction index of R'_w = 52 dB, an additional independent free-standing panel on the inner side of the external wall and on one internal wall in the source room yielded an apparent weighted sound reduction index of R'_w = 56 dB. This indicates that case 2 yielded an improvement of 4 dB.

The furring of two external walls in the receiving room brought a further improvement of 4 dB, yielding a weighted apparent sound reduction index of R'_w = 60 dB.

Finally, adding two more independent panels to the source room yielded a further improvement of 2 dB, resulting in a weighted apparent sound reduction index of R'_w = 62 dB.

The measured sound insulations for the different cases are summarized and listed in Tab. 5-10.

Table 5-10: Measured airborne sound insulation and improvement of the applied treatments to the flanking walls.

Case	Apparent weighted sound reduction index R'_w (C; C_{tr})	*Improvement* $\Delta R'_w$
1	52 (-1; -6) dB	—
2	56 (-1; -4) dB	4 dB
3	60 (-2; -5) dB	4 dB
4	62 (-2; -8) dB	2 dB

Overall, it was observed that the initial R'_w-value of the airborne insulation was 52 dB; after the final improvement, the measured weighted apparent sound reduction index was R'_w = 62 dB.

Each action was documented by calculating the value of R'_w, yielding "$\Delta R'_w$". The measured effectiveness of frequency-dependent airborne sound insulation is depicted in Fig. 5-32. The respective improvements in each frequency range are clear. The treatments on the flanking walls resulted in an almost parallel shift in frequency-dependent airborne sound insulation towards higher values. However, it was observed that below a frequency of approximately 200 Hz, almost no improvement was reached. The reason is that the attached light plasterboard partition to the wall, whose frame is attached to the insulated wall and the width of several centimetres is filled with insulating material does not improve the airborne sound insulation significantly at low frequency. To improve the airborne sound insulation at low frequencies it is needed to increase either mass or width sufficiently. Both treatments were not applicable in that case due to space limitations of the rooms.

On the other hand, Hongisto et al. (2015) stated that airborne sound insulation below 160 Hz seems not to be of primary importance for occupants and hence there might be no real reason to improve the airborne sound insulation at lower frequencies. This result however is in contrast to earlier published results by (Müllner et al., 2007, 2008; Park et al., 2008).

The biggest improvement in sound insulation was observed in the middle and higher frequency ranges. Remarkably, despite these improvements, there were still complaints about insufficient insulation. This is an example of how discrepancies in the new model can be revealed.

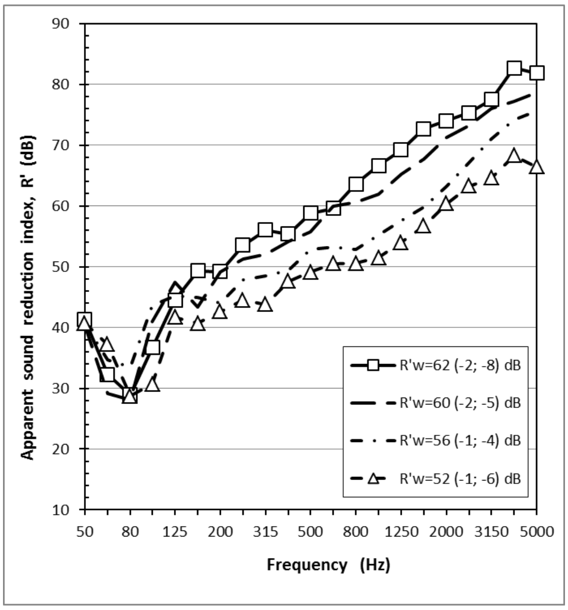


Figure 5-32: Results of the measured airborne sound insulation for each case. R'_w = 52 dB indicates the initial situation without any changes to the flanking walls (case 1).

The measured airborne sound insulations were transformed by a digital filter to simulate damping. The processed signal, using the speech sound signal as a source signal, was used to calculate a loudness level. The calculated loudness level of the receiving level, together with the hearing threshold, is depicted in Fig. 5-33. It is clear that the loudness level of speech was, in all cases, above the threshold. The peak loudness level in the case of 52 dB sound insulation was 16.5 phon, and for 56 dB, it was 15.2 phon. This demonstrates that, in this case, an improvement in sound insulation of 4 dB reduces the loudness level by approximately 1 phon.

The peak value for the sound insulation of 60 dB is 13 phon, and for 62 dB, it is 10.6 phon. It was noted that all of the peak values appear in a frequency range of 400 Hz, which is also the peak value for speech. It is clear that the level drops as sound insulation increases, which is expected; however, even a high airborne sound insulation measurement of 62 dB does not result in a drop of the loudness level to below the hearing threshold. That means that a sound pressure level of 75 dB SPL was audible in the receiving room, even for an R'_w-value as high as 62 dB.

Furthermore, it was noted that the frequency range of the loudness level above the threshold was reduced with increasing sound insulation. The widest frequency range was observed from approximately 250 Hz to 5k Hz for a sound insulation of 52 dB, whereas the smallest frequency range was observed from approximately 315 Hz to 800 Hz for a sound insulation of 62 dB. It is interesting to note that at low frequencies, there was only a small shift towards higher frequencies, whereas at high frequencies, a greater reduction in the frequency range from 5k Hz down to 800 Hz was observed. This shows that an increase in sound insulation primarily influences the sound insulation at higher frequencies.

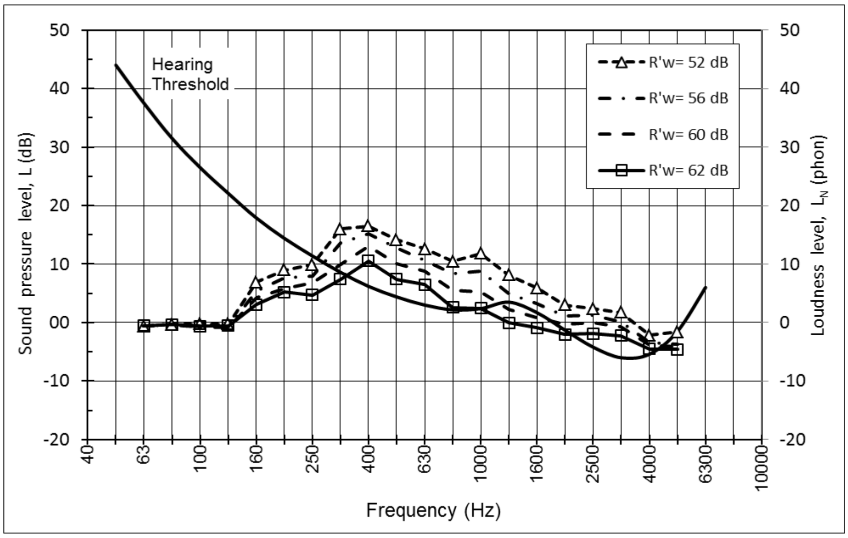


Figure 5-33: Calculated loudness level (L_N) after filtering with the respective airborne sound insulation (R'_w).

The differences in normalized loudness level and in weighted normalized loudness level for the four cases are discussed in detail. For comparison, pink noise is used in addition to speech level because it is commonly used as a test signal in standard procedures to measure airborne sound insulation.

It is therefore of vital interest to know how the broadband noise signal influences these results compared to speech.

The computed idealized airborne sound insulation ($L_{2,0}$) as defined in Eq. (4-4) was obtained by calculating the frequency depending values of the construction and filtering the respective signal yielding the level of interest in terms of a loudness level $L_{N2,0}$. The calculated weighted sound reduction index is R_w = 64 (-2; -6) dB.

In Fig. 5-34, the normalized level difference and the weighted normalized level difference for different airborne sound insulations are shown.

From comparison, it is clear that there is little difference between the different sound signals if the level difference is considered. The higher the single value of the airborne sound insulation, the closer the normalized loudness level difference comes to unity (i.e., the measured and predicted airborne sound insulation values match).

It was noted that the normalized level difference did not differ significantly between the two signals.

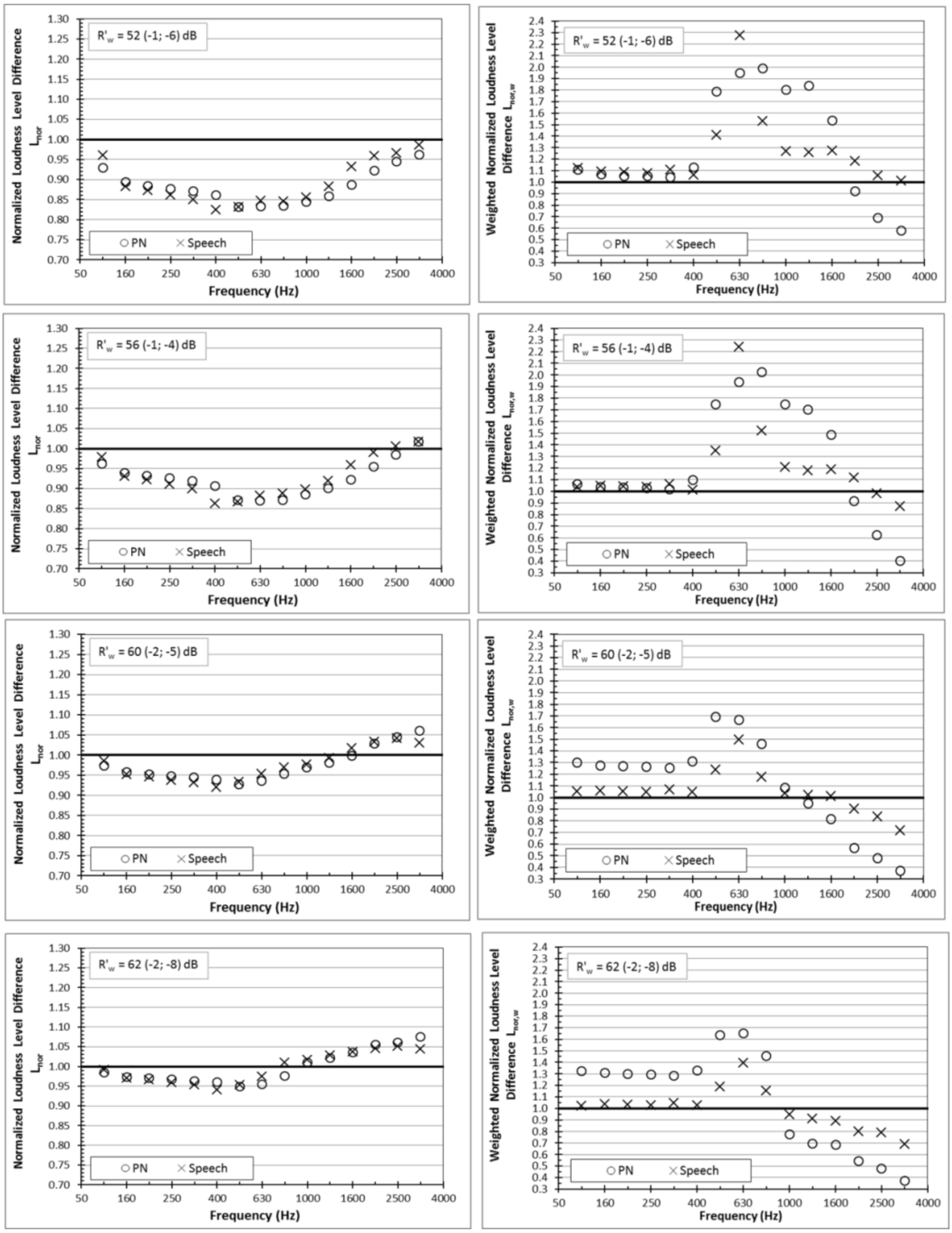


Figure 5-34: L_{nor} and $L_{nor,w}$ according to Eq. (4-6) and (4-10) for different R'_w-values. The source sound signal was 75 dB SPL for both, pink noise (PN) and speech level (Speech).

When the normalized loudness level difference is weighted, a clear change is observed. As the sound insulation increases, the weighted normalized loudness level difference decreases; however, it was observed that for speech and low sound insulation, the peak value was higher than when pink noise was used as a source signal (see Fig. 5-34). This indicates that the spectrum of the signal is vital for the calculated results and the weighted normalized loudness level difference.

In addition, for the frequency range above the threshold, there was a reduction in loudness with increasing sound insulation. The widest frequency range was observed between approximately 400 Hz and 2,000 Hz for a sound insulation of 52 dB, whereas the smallest frequency range was observed between approximately 400 Hz and 1,000 Hz for a sound insulation of 62 dB.

It is interesting to note that at low frequencies, there was no shift towards higher frequencies, whereas at high frequencies, a greater reduction in the frequency range from 3,150 Hz down to 1,000 Hz was observed. This confirms the previously reported result (Neubauer and Kang, 2014 b) that an increase in sound insulation primarily affects higher frequencies.

In order to compare the calculated values with the new approach, single values of the normalized loudness level difference and weighted normalized loudness level differences were calculated by applying Eq. (4-7) and (4-11). The results are depicted in Fig. 5-35 a,b.

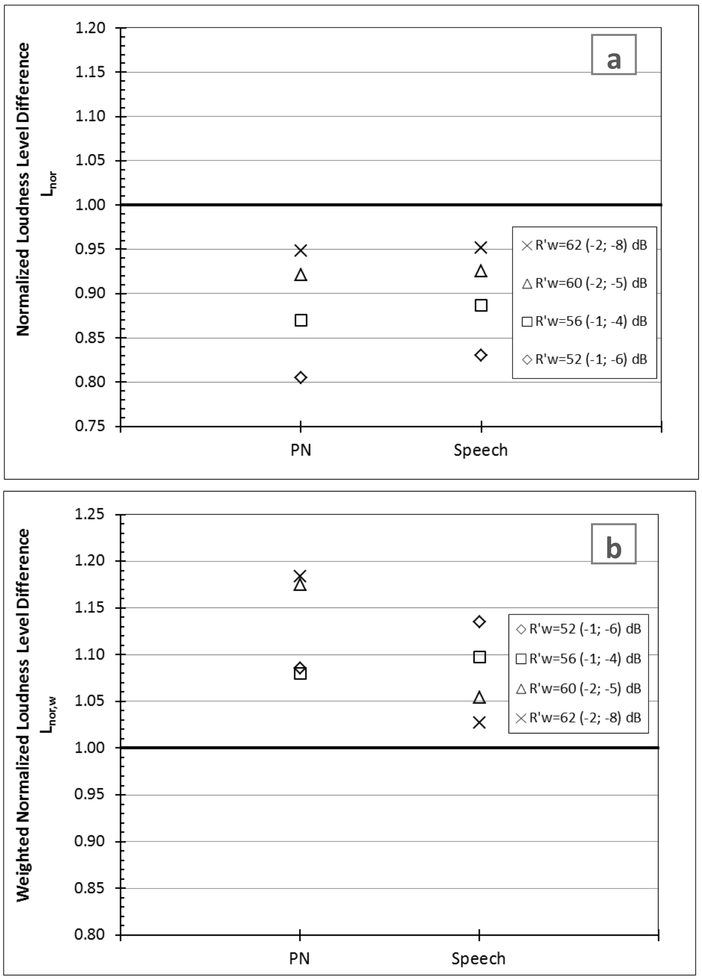


Figure 5-35: Calculated normalized loudness level difference (a) and weighted normalized loudness level difference (b) according to Eq. (4-7) and (4-11) for different R'_w-values. The source sound signal was 75 dB SPL for both, pink noise (*PN*) and speech level (*Speech*).

Figure 5-35 a shows that the normalized loudness level difference (L_{nor}) does not discriminate between the two sound signals; however, it is clear that the difference in the airborne sound insulation is in agreement with the increasing R'_w-values. In Fig. 5-35 b, an inverted picture is drawn comparing the normalized loudness level difference (L_{nor}) and the weighted normalized level difference ($L_{nor,w}$). It is observed that pink noise yields a grouped result (i.e., low sound insulation causes greater values than higher sound insulations). This means the values R'_w = 52 dB and 56 dB show close results, which was also seen for R'_w = 60 dB and 62 dB. This is in line with the results in the literature showing that pink noise has little fluctuation strength (Neubauer and Kang, 2013), and hence, its influence decreases with increasing sound insulation. This result, however, does not hold for speech, and it is seen in Fig. 5-35 b that the weighted normalized loudness level difference ($L_{nor,w}$) clearly discriminates between different sound insulations. This correctly depicts the influence of increasing airborne sound insulation.

These results indicate that the best value is the highest numerical value; that is, an R'_w-value of 52 dB is predicted to have the lowest sound insulation effect, while an R'_w-value of 62 dB is predicted to have the highest sound insulation effect. The results of a related subjective assessment imply that sound will still be heard because the value is not unity. In Fig. 5-36, the calculated relative improvement in sound insulation with reference to 52 dB is depicted.

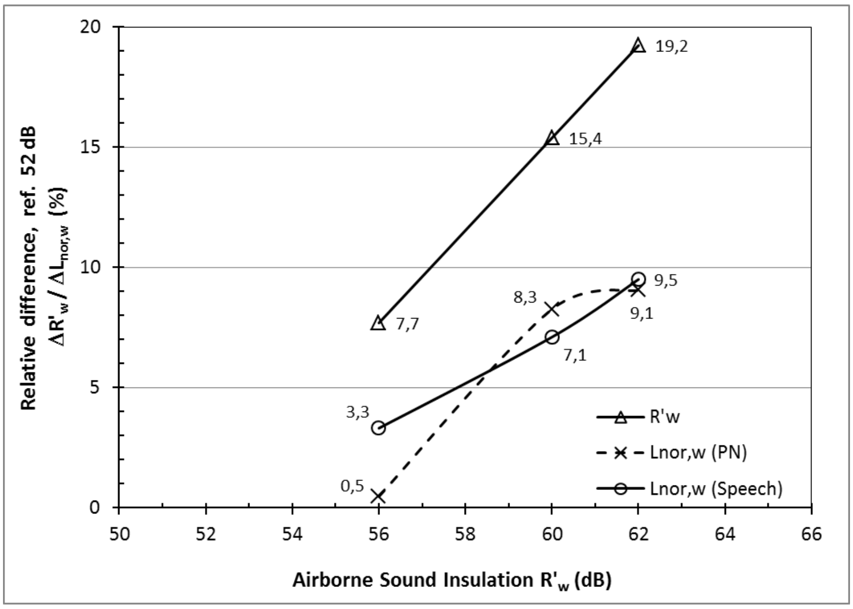


Figure 5-36: Relative difference of R'_w and $L_{nor,w}$ for different airborne sound insulations with ref. 52 dB. (PN) indicates source signal pink noise and (Speech) indicates source signal speech.

It is seen that improving the airborne sound insulation in three steps [i.e., (52-56 dB), (56-60 dB), and (60-62 dB)] increases the related R'_w values linearly, whereas the introduced weighted normalized loudness level difference ($L_{nor,w}$) does not appear to be linear.

While the standard method for calculating the R'_w-value revealed a linear improvement for each step of increased airborne sound insulation of approximately 8, 15, and 19%, the weighted normalized loudness level difference method yielded values for $L_{nor,w}$ *(PN)* of around 1, 8, and 9% and for $L_{nor,w}$ *(Speech)* of around 3, 7, 10%, respectively.

Furthermore, the model discriminates well between the two sound signals. The airborne sound insulation, expressed as an R'_w-value, is not proportional to the $L_{nor,w}$ value, which is in agreement with perception theory. This non-linear dependence of the two values indicates that a simple increase in a certain airborne sound insulation value does not automatically lead to the same numerical increase of a subjective assessment of the sound insulation.

It is interesting to note that in the case of less airborne sound insulation, the difference of the relative improvement between both signals is larger than for higher sound insulation.

At an airborne sound insulation of 62 dB, almost no difference between pink noise and speech is reported. This is an indication that the fluctuation of a signal becomes depressed in the presence of higher sound insulation, which is reasonable because higher sound insulation reduces favourably at higher frequencies. This is in line with data presented in Fig. 5-34, where it was seen that greatest reduction in the $L_{nor,w}$-value was at higher frequencies.

5.3.2 Case distinction of the six conditions for $L_{nor,w}$

In this section, distinctions between the six conditions of Eq. (4-11) are demonstrated. To this end, two different examples are investigated.

First, the results of theoretical calculations for different airborne sound insulations are depicted and compared. In this investigation, findings for the same material but different airborne sound insulation are compared. Second, the airborne sound insulations investigated in section 5.2.3 (see Fig. 5-15) are examined and compared. From this investigation, important findings regarding the equal airborne sound insulation were obtained.

5.3.2.1 Different Airborne Sound Insulation

In this section, different concrete airborne sound insulations of different thicknesses are investigated. The calculated airborne sound insulations are depicted in the previous section in Fig. 2-9, and the detailed calculation values are depicted in Appendix XI.

For this investigation, data required for an unbiased evaluation of airborne sound insulation was not available; hence, a simplified expression was used, though with little loss of accuracy because the objective was to obtain a probability measure of differences. The most obvious first step is to assume that the hypothetical airborne sound insulation follows the frequency dependent values of the reference curve, according to ISO 717. The reference values (L_0) used to compute the difference in weighted normalized loudness level difference ($L_{nor,w}$) were taken from the shifted reference curve given in ISO 717-1 as a substitute for an “unbiased” construction. That is, the calculated *R*-value and the shifted *R*-value of the reference curve were taken to form the filter function to process the signal. In Appendix XI the calculated values of the parameters, in particular R_w (C; C_{tr}) and $L_{nor,w}$, are depicted for a single wall construction of concrete with a thickness ranging from 100 mm to 400 mm in 50 mm increments. By comparison, it is clear that the $L_{nor,w}$ value decreases with thickness. In section 4.3, it was shown that Eq. (4-11) is case sensitive (i.e., $L_{nor,w}$ depends on the individual results of the level differences and the weighting).

Again, the following regions occur depending on the six conditions:

I) $L_{nor} > 1 \wedge w > 1 \Rightarrow L_{nor,w} > 1$

II) $L_{nor} < 1 \wedge w < 1 \Rightarrow L_{nor,w} < 1$

III) + IV) $L_{nor} > 1 \wedge w < 1 \Rightarrow L_{nor,w} < 1 \vee L_{nor,w} > 1$

V) + VI) $L_{nor} < 1 \wedge w > 1 \Rightarrow L_{nor,w} < 1 \vee L_{nor,w} > 1$

In searching for an airborne sound insulation that fulfils the conditions *I* to *VI*, it was observed that a certain airborne sound insulation is sensitive to the excitation (i.e., the type of sound signal applied). Therefore, in fulfilling certain criteria, the source signal must be considered as well.

In Tab. 5-11, examples of the calculated sound reduction index R_w (C; C_{tr}) for different regions of the six different conditions yielding the difference in weighted normalized loudness level ($L_{nor,w}$) are presented for comparison. Appendix XII shows the results of Tab. 5-11 in detail. It can be seen that the sound reduction index R_w, as well as the C and C_{tr} values, differ depending on the sound sample used.

This is a strong indication that the specific fluctuation strength significantly influences the result of computing the weighted normalized loudness level difference.

Table 5-11: Examples of calculated sound reduction index R_w (C; C_{tr}) for the different regions of the six different conditions yielding the weighted normalized loudness level difference $L_{nor,w}$.

Region	L_{nor}	*w*	$L_{nor,w}$	R_w (C; C_{tr})	*Sound*	*Construction*
I	>1	>1	>1	65 (-2; -6)	PN, WN	300 mm concrete
II	<1	<1	<1	54 (-1; -4)	PS	150 mm concrete
III	>1	<1	<1	49 (-1; -3)	PS	100 mm concrete
IV	<1	>1	<1	59 (-2; -5)	PN, B, E	200 mm concrete
V	<1	>1	>1	69 (-2; -6)	PN, E, PS	400 mm concrete
VI	>1	<1	>1	50 (-1; -1)	WN, B	—

Combining all of the results for the single wall construction with a thickness in the range of 100 mm to 400 mm for different source signal types reveals that some spreading of the weighted normalized loudness level difference occurred. This can be seen in Fig. 5-37, where the upper and lower bounds of the results are shown. In Fig. 5-37, it can be seen that the wall construction shows the best results for all values of the airborne sound insulation for the transient signal “Eminem”, for which the smallest variation was observed. The calculated mean and standard deviation are 1.046 ± 0.012.

The results for the transient signal “party sound” were all less than unity, which indicates that the sound signal is perceived to be louder than predicted. However, for high sound insulation, the construction yields the closest values to unity for that signal type. Interestingly, the smallest sound insulation (i.e. 49 dB) yielded the worst rating (i.e., the smallest $L_{nor,w}$ value). This is an indication of the potential for disruption of that sound sample.

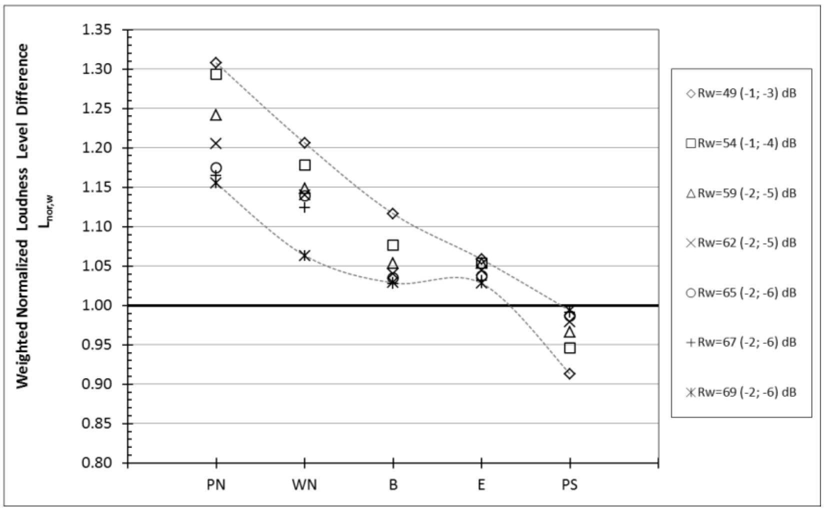


Figure 5-37: Weighted normalized loudness level difference ($L_{nor,w}$) for different sound samples calculated for a concrete wall having thickness of 100 mm up to 400 mm in steps of 50 mm and calculated sound reduction index R_w (C; C_{tr}). The upper and lower dotted grey line indicates the region for the individual results.

In addition, the broadband noise signals “pink noise” and “white noise” show the highest values of $L_{nor,w}$ for all concrete wall thicknesses. However, following the logic of this model, this indicates that the results are not reliable with respect to subjects’ perception. The broadband noise signals do indicate that sound insulation performs better than predicted by subjective assessment. Furthermore, it was observed that the broadband noise results are greater than unity for all R_w-values, indicating that the sound insulation is supposed to be greater than calculated. This could be because the “biased” airborne sound insulation is perceived to be greater than the “unbiased” or predicted value.

In the subjective test, it was found that white noise is judged to be overall quieter than the other sound samples (see Fig. 5-12). It was concluded that, in this study, white noise as a test signal causes a perceived fictive increase in the airborne sound insulation.

5.3.2.2 Equal Airborne Sound Insulation

The airborne sound insulation with an equal single number value but different *C* and C_{tr} values, respectively, is depicted in section 5.2.3 in Fig. 5-15. The detailed airborne sound insulation curves of the respective airborne sound insulations are also shown in Appendix VIII, b). The detailed results are depicted in Appendix XIII, a) to e).

In Appendix XIII b) and c), the frequency-dependent normalized loudness level difference, the weighting, and the weighted normalized level difference for cases *I* to *IV* are shown. The loudness level difference does not differ between the sound signals. A large spread, however, was observed for the weighted normalized loudness level difference. The smallest deviation was observed for case *II*.

From comparing the apparent sound reduction index R_w as depicted in Appendix VIII b), it is obvious that the frequency curve is rather even (i.e., no distinct frequency dip is observed in the sound insulation curve).

In Figs. 5-38 and 5-39, the results of the normalized and the weighted normalized loudness level differences (L_{nor}, *and* $L_{nor,w}$) are shown. Although the single numerical values for airborne sound insulation are identical, the normalized loudness level difference and the weighted normalized loudness level difference deviate considerably with the signal type applied.

Figure 5-38 reveals that white noise shows the smallest deviation, followed by pink noise. The music type signals showed the greatest spread.

It is interesting to note that depending on the sound signal, the normalized loudness level difference is either above or below unity. However, inspection of the detailed results (see Appendix XIII, d) reveals that case I, [i.e. R_w = 50 (-1; -1) dB], shows highest values for all sound samples. The calculated mean and standard deviation for the case "*I*" are: 1.090 $\pm$ 0.027.

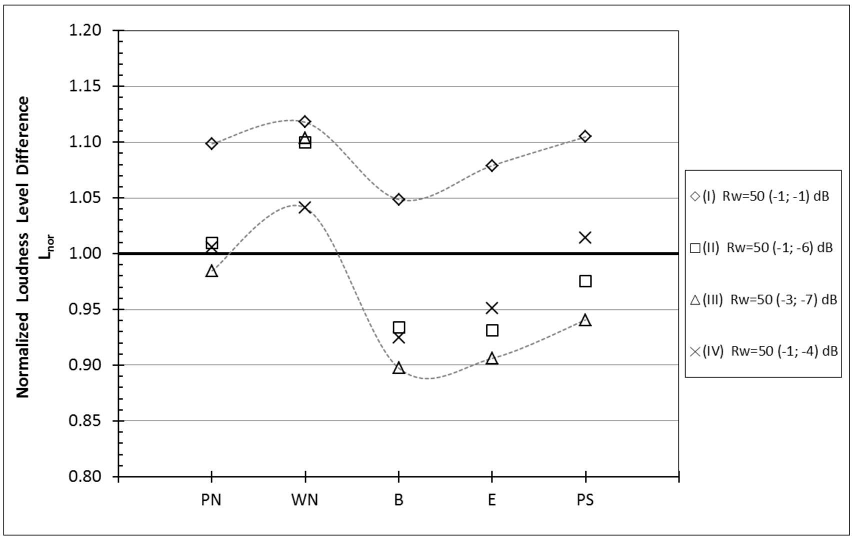


Figure 5-38: Normalized loudness level difference (L_{nor}) grouped in sound samples for different cases "*I* to *IV*" of R_w = 50 (C; C_{tr}) dB. The upper and lower dotted grey line indicates the region for the individual results.

The shape of the grey line depicted in the figures depends on the arrangement of the sound samples at the abscissa. The area between the upper and lower grey line indicates a probability area where the respective normalized level difference should be, depending on the sound sample. It is therefore a good visualization of how the normalized loudness level difference deviates for different C and C_{tr} values with a constant R_w-value.

In Tab. 5-12, the normalized loudness level differences (L_{nor}), the mean and the standard deviation of different sound samples are presented.

Comparing the values in Appendix XIII, b) and c), it is clear that the frequency-dependent normalized loudness level differences do not result in great differences for different sound signals. The single values for the loudness level difference, however, differ for different sound signals.

<u>Table 5-12</u>: Normalized loudness level difference (L_{nor}) grouped in sound samples for different cases "*I* to *IV*" of R_w = 50 (C; C_{tr}) dB.

R_w = 50 dB	Normalized loudness level difference (L_{nor}) for different sound samples				
Case of C / C_{tr}	PN	WN	B	E	PS
I	1.099	1.118	1.049	1.079	1.105
II	1.010	1.100	0.934	0.931	0.975
III	0.985	1.104	0.897	0.906	0.941
IV	1.006	1.041	0.925	0.951	1.014
Mean	1.025	1.091	0.951	0.967	1.009
Standard dev.	0.050	0.034	0.067	0.077	0.071

The weighted normalized loudness level difference ($L_{nor,w}$) grouped in sound samples for the four cases are shown in Fig. 5-39.

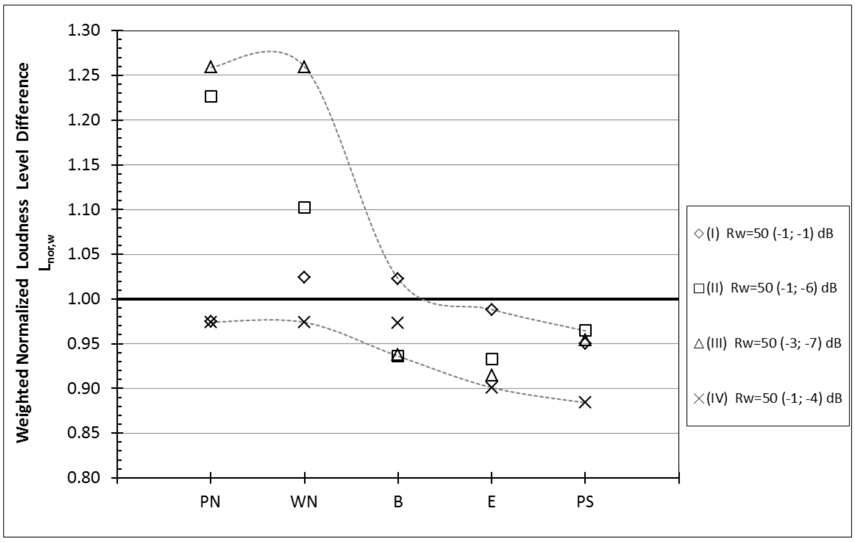


Figure 5-39: Weighted normalized loudness level difference ($L_{nor,w}$) grouped in sound samples for different cases "*I* to *IV*" of R_w = 50 (C; C_{tr}) dB. The upper and lower dotted grey line indicates the region for the individual results.

From Fig. 5-39, it can be observed that broadband noise signals spread most and show high values above unity, indicating a better subjective assessment of airborne sound insulation than theoretically expected. In contrast, transient sound signals spread much less than broadband noise signals but did yield results below unity. This indicates that the effect of airborne sound insulation was less than theoretically expected. This is thought to be due to the perception of music or other music-like signals as intrusive noise. In Tab. 5-13, the weighted normalized loudness level differences ($L_{nor,w}$), the mean and the standard deviation of different sound samples are presented.

Table 5-13: Weighted normalized loudness level difference ($L_{nor,w}$) grouped in sound samples for different cases "*I* to *IV*" of R_w = 50 (C; C_{tr}) dB.

R_w = 50 dB	Weighted normalized loudness level difference ($L_{nor,w}$) for different sound samples				
Case of C / C_{tr}	PN	WN	B	E	PS
I	0.975	1.024	1.023	0.988	0.950
II	1.227	1.102	0.936	0.933	0.964
III	1.260	1.259	0.938	0.915	0.954
IV	0.974	0.974	0.973	0.901	0.884
Mean	1.109	1.090	0.967	0.934	0.938
Standard dev.	0.156	0.125	0.041	0.038	0.037

Notably, case "*IV*" was less than unity for all sound samples, indicating that this airborne sound insulation is perceived as less "protective" than expected or calculated. Overall, the airborne sound insulation in case "*I*" showed the best results for all sound samples, meaning that the airborne sound insulation of R_w = 50 (-1; -1) dB yielded results for all sound samples close to unity. The airborne sound insulation of the construction groups "*II*" and "*III*" were the worst, meaning that spreading was highest for different sound signals, indicating that the predicted airborne sound insulation was subjectively overrated.

It is interesting to examine the construction case itself (i.e., for a constant R_w = 50 (C; C_{tr}) dB but different sound signals) and how the normalized and the weighted normalized loudness level differences (L_{nor}, $L_{nor,w}$) performed. Depending on the "case group", the normalized loudness level difference was either above or below unity. However, inspection of the detailed results (see Appendix XIII, e)) reveals that case "*I*" (i.e., R_w = 50 (-1; -1) dB) showed the smallest deviations for all sound samples. The calculated mean and standard deviation for case "*I*" for the normalized loudness level difference are: 1.090 ± 0.027.

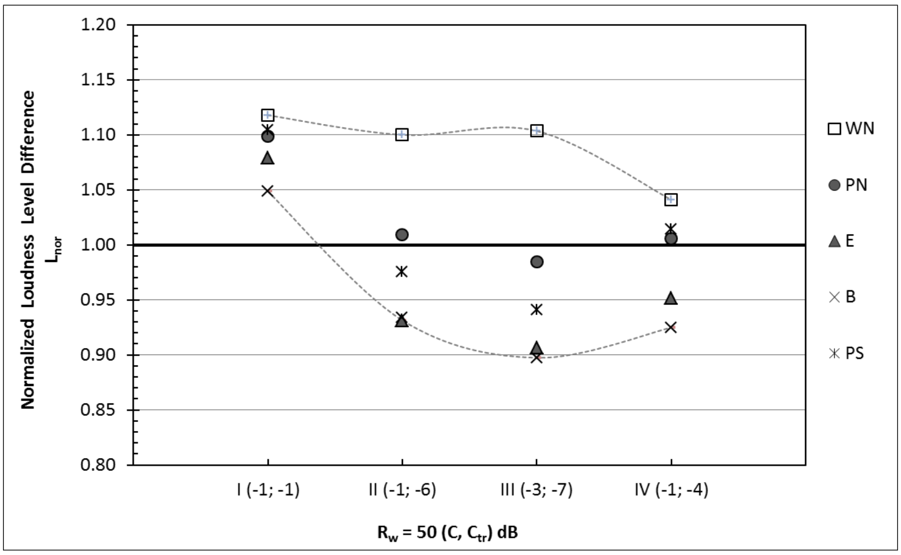


Figure 5-40: Normalized loudness level difference (L_{nor}), grouped in cases "*I* to *IV*" of R_w = 50 dB with varying spectral adaptation terms C and C_{tr} for different sound samples The upper and lower dotted grey line indicates the region for the individual results.

In Tab. 5-14 presents the normalized loudness level differences (L_{nor}), the mean and the standard deviation of the different sound samples presented.

<u>Table 5-14</u>: Normalized loudness level difference (L_{nor}) for different sound samples grouped in cases "*I* to *IV*" of R_w = 50 (C; C_{tr}) dB.

R_w = 50 dB	Normalized loudness level difference (L_{nor}) for different cases of C / C_{tr}			
Sound samples	I (-1; -1)	II (-1; -6)	III (-3; -7)	IV (-1; -4)
WN	1.118	1.100	1.104	1.041
PN	1.099	1.010	0.985	1.006
E	1.079	0.931	0.906	0.951
B	1.049	0.934	0.897	0.925
PS	1.105	0.975	0.941	1.014
Mean	1.090	0.990	0.967	0.987
Standard dev.	0.027	0.069	0.084	0.048

Comparing the frequency-dependent values presented in Appendix XIII, b) and c), it is clear that the frequency-dependent normalized loudness level difference does not differ greatly for different sound signals.

The single values of the loudness level difference do, however, differ for different sound signals. The weighted normalized loudness level differences ($L_{nor,w}$) for the four cases are shown in Fig. 5-41. In Tab. 5-15, the means and the standard deviations for different sound samples of the weighted normalized loudness level differences ($L_{nor,w}$), are presented.

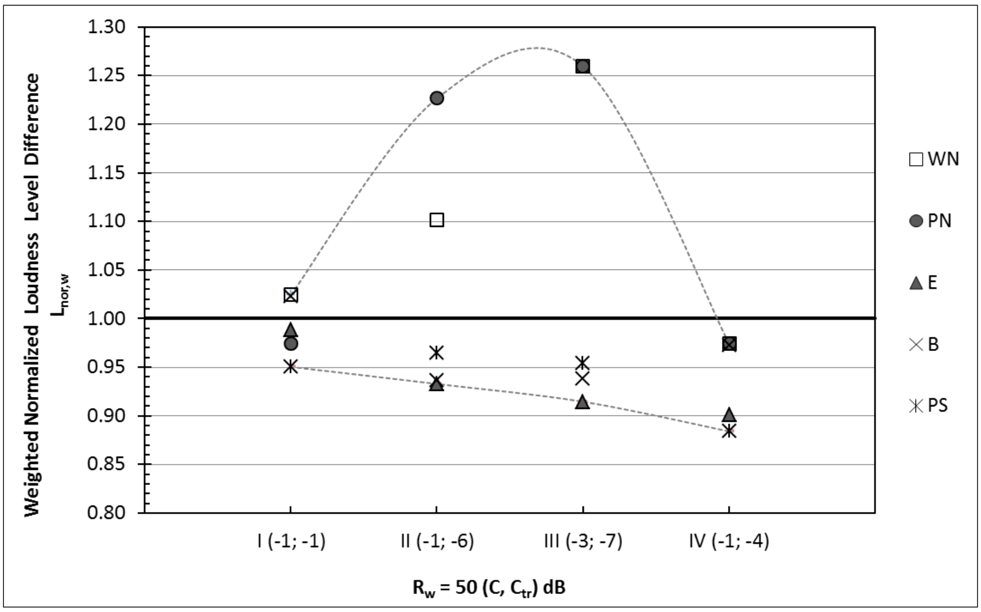


Figure 5-41: Weighted normalized loudness level difference ($L_{nor,w}$), grouped in cases "*I* to *IV*" of R_w = 50 (C; C_{tr}) dB for different sound samples The upper and lower dotted grey line indicates the region for the individual results.

Table 5-15: Weighted normalized loudness level difference ($L_{nor,w}$) for different sound samples grouped in cases "*I* to *IV*" of R_w = 50 (C; C_{tr}) dB.

R_w = 50 dB	Weighted normalized loudness level difference ($L_{nor,w}$) for different cases of C / C_{tr}			
Sound samples	I (-1; -1)	II (-1; -6)	III (-3; -7)	IV (-1; -4)
WN	1.024	1.102	1.259	0.9740
PN	0.975	1.227	1.260	0.9741
E	0.988	0.933	0.915	0.9010
B	1.023	0.936	0.938	0.9728
PS	0.950	0.964	0.954	0.8841
Mean	0.992	1.032	1.065	0.941
Standard dev.	0.032	0.129	0.178	0.045

Notably, case "*IV*" is smaller than unity for all sound samples. This indicates that this sound insulation is thought to be less "protective" in a subjective sense than expected or calculated. Overall, the airborne sound insulation of case "*I*" shows the best result for "Beethoven" as a sound sample, meaning that the airborne sound insulation of R_w = 50 (-1; -1) dB yielded results for that sound sample above and close to unity. Inspection of Tab. 5-15 as well as the detailed results (see Appendix XIII, e) reveals that case "*I*" shows a calculated mean and standard deviation of: $L_{nor,w} = 0.992 \pm 0.032$. The airborne sound insulation of groups "*II*" and "*III*" was the worst, meaning that the spreading was highest for different sound signals (see Fig. 5-41) and indicating that the predicted airborne sound insulation was overrated compared to the measured value.

In conclusion, the construction with an airborne sound insulation of R_w = 50 (-1; -1) dB performs best independent of the type of sound signal applied, in terms of the model interpretation. This does, however, imply that the calculated or theoretically predicted airborne sound insulation is likely to perform as subjectively expected. This does not mean that the airborne sound insulation would subjectively be judged sufficient to avoid annoyance, but implies that the calculated sound insulation is close to the subjective sound insulation.

5.4 Conclusions

This section discussed the newly introduced model in terms of objective and subjective measurements of different sound signals and different airborne sound insulations. In this chapter, the model was validated with three objectives:

First, the behaviour of the model was investigated by applying different sound signals (i.e., steady- and non-steady-state signals).

As was shown in the previous chapter, the model is sensitive to the test signal as proven through measurements. In this chapter, it was demonstrated that for different sound signals, a simple sound pressure level difference does not correlate sufficiently with subjective assessments. In this chapter, the investigated sound signals are shown in detail and are differentiated into two groups: steady-state signals and non-steady-state signals. These signals were investigated in terms of various psychoacoustical parameters. From these investigations, it is shown that the psychoacoustical survey measures of specific roughness and tonality yield zero values for high sound insulation and are therefore omitted from further investigations in this research. Sharpness - another important psychoacoustic measure used to describe a sound signal - was also omitted due to the fact that it shows the highest values for broadband noise signals compared to music type signals. This result was unexpected because sharpness is usually a measure of the high frequency content of a sound. However, to assess construction in terms of transmission loss, sharpness was classified as an unsuitable predictor. Furthermore, it is shown that loudness level derived from different sound signals was not linearly related to sound pressure level, underlining the hypothesis that sound pressure level differences do not correlate well with the subjective assessment of airborne sound insulation measures. The method used to simulate the transmission loss (i.e., the airborne sound insulation) electronically was proven to be reliable. The calculated error depended on the signal used as an excitation by less than 3%. An investigation of the specific fluctuation strength revealed that broadband noise signals have little fluctuation strength, as expected, but non-steady-state signals show a non-linear dependence on sound pressure level. Furthermore, it was shown that, depending on the time spectra of the signal, fluctuation strength rose steeply with increasing sound pressure level. In addition, it was shown that specific fluctuation strength depends significantly on the frequency spectra of the signal.

Second, the model was validated by applying subjective tests (section 5.2). It was shown that, depending on the level of sound insulation, the different sound signals were judged differently. The subjective tests also conducted revealed that the type of sound signal was judged differently if the sound insulation was constant, supporting the findings of the pilot survey. It was also shown that white noise was judged to be heard “quieter” compared to the other sounds investigated.

The difference in frequency-dependent airborne sound insulation for different excitation signals was investigated subjectively, which revealed that certain constructions with the same numerical rating (R_w-value) are judged to be subjectively different.

Third, the implementation of the model in section 5.3 shows that the model correctly depicts frequency dips in the sound insulation curve. To validate the model on characterized constructions, measurements of various sand-lime bricks were taken, and the results support that the model is sensitive to the type of excitation signal. The presented investigation supports the findings of the previous sections. This shows how the model behaves with regard to different airborne sound insulations and how it depicts various improvements in airborne sound insulation on the same structure.

Finally, the case sensitivity of the model is specified and shows how the model can be used to investigate a structure to yield the best results for a specified excitation. This result determined the “best” construction for a certain sound signals (where “best” means that an expected result correlates highly with a hypothetical reference value).

6 DISCUSSIONS

This research aimed to improve the assessment of airborne sound insulation by combining objective and subjective measures. The procedure for calculating airborne sound insulation as provided by the European standard EN 12354, which was the basis for the international standard ISO 15712, as well as the procedure for measuring airborne sound insulation according to the international standard ISO 16283 in association with the international standard ISO 717-1, yields single number ratings. These ratings are especially suitable for comparing the performance of alternative building products, materials, and product data and to formulate requirements given in Building Regulations as needed for dwellings, flats, houses and other habitations where people live in adjacent rooms. However, these ratings, as the literature review and results presented in this work show, are not suitable for comparing the perceived efficacy of insulation.

Although the debate about the correlation of an airborne sound insulation and its subjective assessment is long and well documented in the literature, as shown in Chapter 2, three further points needed to be discussed:

- To identify the differences between design predictions and the measured performance of the case study building
- To assess the role of the tools used in the prediction and analysis of airborne sound insulation
- User Needs and Expectations

6.1 To Identify the Differences between Design Predictions and the Measured Performance of the Case Study Building

Based on the results and analysis in this thesis, it is feasible to use standardized building assessment methods to evaluate a building's performance. To compare calculated and measured data, the calculation scheme highlights differences in calculation and measurement results. It is therefore useful examining the residual differences more closely in order to recognize real performance problems. By aligning the calculation scheme as closely as possible with real situations and conditions in buildings, a valuable tool for finding performance problems is obtained. This work describes a key novel concept that enables the adjustment of the calculation scheme such that it matches actual building conditions as closely as possible. The two main contributions of this work are the airborne sound insulation performance comparison methodology and the subjective performance assessment procedure that integrates two perspectives (R_w-value and valuation). The calculation scheme allows an assessor to identify a larger number of performance problems in less time per performance problem compared with other standard methods by comparing measured and simulated airborne sound insulation performance data. The case study partition showed a measured airborne sound insulation of 52 dB and an idealized airborne sound insulation of 64 dB. After improvements to the flanking constructions, the airborne sound insulation was raised to 62 dB.

Overall, these results indicate that the performance gap is the result of comparing three variables: a design prediction, empirical evidence, and an assessment by the resident. This leads to a challenge in performance prediction, but it is important to consider how much sound protection a building is likely to need.

6.2 To Assess the Role of the Tools used in the Prediction and Analysis of Airborne Sound Insulation

The result of predicted airborne sound insulation by a partition reflected the construction information well, although the case study demonstrates that having an accurate idea of actual use and occupant patterns at the design stage is not necessarily sufficient to close the performance gap. Whilst the airborne sound insulation prediction may be more representative of how the building will function during use, the total prediction is thought to always be higher than reality due to activities of the inhabitants. Thus, signals that focus on the building designer and how they will use their tools may be more beneficial.

This work has shown that a thorough prediction model can provide a better estimate of measured airborne sound insulation if the likely operation of the building is considered. However, in the case study, the airborne sound insulation was overestimated compared to the subjective expectation, warranting further investigation.

Although this new approach has proven to be a useful design tool, it lacks a sufficiently large quantity of data to inform benchmarking or future design processes. Much more in-use data, compared back to design predictions, is needed. It is thought that in the near future, it will be possible to simulate and accurately measure the room and building acoustic parameters, which will enable the implementation and use of simulation and measurement algorithms in prediction models to simulate the subjective experience of airborne sound insulation.

The use of psychoacoustic parameters in sound design is well established, as are sound quality assessments. However, no link exists to assess a sound in a room that comes from a neighbour’s activity or even from the outside. This could be implemented in auralization programs, which enable modelling of the sound signals flowing through the building and to the receiver. A recording of the sound level at the site of future construction enables the architect to judge the residual sound level in the finished building. The auralized sound can thus be used in the present model, opening the possibility of demonstrating effects and for teaching and investigating sound effects by variation of construction parameters.

6.3 User Needs and Expectations

Leaman (Chapter 10 in: Cole and Lorch, 2003) states: "S*ince the early 1990s, Building Use Studies has carried out 150 studies of buildings, mainly from the point of view of their occupants but also often including their environmental and technical performance. Inevitably, the question of global similarities and differences arises, especially in terms of building users' attitudes and preferences but also in comparisons between the buildings themselves.*"

In general, there are problems with controlling for context; that is, as Leaman pointed out: "*operating circumstances are so different from one case to the next that it is often impossible to be sure that an accurate comparison is being made. There is too much uncontrollable (in the statistical sense) variation, and the data are thus too "noisy" to be able to draw firm conclusions*." In addition, the complexity of buildings as total systems should also be considered.

Leaman finally states: "*that the likes and behaviours of "ordinary" building occupants who use and work in buildings every day but usually have no active part in designing or managing them all have different needs and expectations*."

As Cooper (1982) explains, comfort standards are "*social constructs which reflect the beliefs, values, expectations and aspirations of those who construct them*".

Even if some evidence is given that indoor environments might converge to an overall accepted value, literature shows that efficiency, wellbeing, and satisfaction are strongly related to comfort. In other words, the better occupants think the indoor environment is, the more likely they are to say that they are productive, healthy and happy. Leaman concluded: "*Unwanted noise in a building is often a symptom of poor design-team and management integration*."

Annoyance or noise awareness is an overall evaluation of disturbances and unpleasantness of noise in general and is therefore subjective; thus, the social and cultural backgrounds of occupants have an important influence on their subjective attitudes to noise and must be considered in addition to physical parameters. Therefore, the complexity of an awareness of noise yielding to annoyance and the description of a certain airborne sound insulation, which means more than only the determination of annoyance, cannot be simply described with a single parameter because many factors contribute to it.

Hence, individual, contextual or physical variables causing a deviation from a simple average measure such as a single number rating must be determined with respect to an improved understanding of annoyance as caused by neighbouring noise.

It is demonstrated especially well in this work by comparing objective and subjective measures that a single number does not encompass the subjective impression of a heard sound. This is in contrast to results published recently by Ljunggren et al. (2014), who asked study participants to rate annoyance and derived a correlation between the rated airborne sound insulation and ($R'_w + C_{50\text{-}3150}$). This result might be inaccurate due to the structure of the questionnaire because results of a survey are probably much more reliable using "unobtrusive measures" than asking participants direct questions (Buckingham and Saunders, 2009).

By comparing constructions with equal numerical values of airborne sound insulation, as shown in Figs. 5-15 and 5-16, it can be seen that different frequency-dependent airborne sound insulations yielding the same single number rating perform differently when judged subjectively. In particular, the results depicted in Fig. 5-16 demonstrate that a single numerical value does not correlate with subjective assessments.

This work showed that different sound samples are judged differently in their loudness. That is, music-like sound samples were assessed to be louder than broadband noise sound samples. This result is presented in Fig. 5-13. The hearing tests conducted in this work, however, are limited in that sense, that no analysis of gender, age and cultural differences were made, which could be considered for future work.

The model presented in Chapter 4 provides a link for building a measure that is both objective and subjective to ensure that sound insulation fits a certain demand. This loudness based model must compute the loudness level difference and the specific fluctuation strength. To compute the level difference, the sound pressure level at the source and receiver must be transformed into a loudness level. The example in Fig. 5-18 shows that the normalized loudness level difference and the weighted normalized loudness level difference, as shown in Fig. 5-20, depict very well the event of a single frequency dip. However, it was observed that the reverse picture is drawn when comparing the normalized loudness level difference and the weighted normalized level difference, an indication that the specific fluctuation strength significantly influences the weighted normalized loudness level difference.

By definition, the normalized loudness level difference according to Eq. (4-6) reveals that results greater than one (L_{nor} > 1) indicate a tendency that theoretical values in comparison to measurements are overestimated and vice versa. And as demonstrated in

Fig. 5-18, a dip in the frequency depending normalized loudness level difference (L_{nor}) yield values smaller than one indicating that the measured or biased loudness level (L_m) is greater than the unbiased or calculated value (L_0). This yield a smaller measured or biased sound reduction index (R_w) compared to the calculated or unbiased R_w-value.

The analysis of the weighted normalized loudness level difference according to Eq. (4-10) reveals, on the other hand, that results cannot be interpreted without looking closer to the weighting (w). There are only two cases which makes it possible to give a statement about the tendency of the results. In detail this is if both values of (L_{nor}) and (w) are greater or less than unity. All other cases as depicted in chapter 4, i.e. case III to VI, are undetermined. Case I, where $L_{nor,w} > 1$, suggests that the measured or biased loudness level is smaller than the predicted or unbiased loudness level yielding results supposing that a measured sound reduction index compared to the predicted value overestimates the sound insulation. The other way around is given for case II.

As was shown by a case study of measured improvements in a construction, the model pictures these improvements well. By comparing the computed results in Fig. 5-34, it is demonstrated that the normalized loudness level difference does not differentiate between different sound signals, whereas the weighted normalized loudness level difference shows a significant difference in the frequency range. The calculated numerical value as depicted in Fig. 5-35 demonstrates very well that the model distinguishes between the different sound signals for different airborne sound insulations and correctly depicts the influence of increasing airborne sound insulation.

Additionally, the model differentiates well between broadband noise signals, music-like signals, and speech, which is demonstrated in Fig. 5-35 b. The linear relationship of the airborne sound insulation value and the near linearity of the normalized loudness level difference are shown through the function presented in Fig. 5-36, while it is clear that the weighted normalized loudness level difference is not a linear function. The airborne sound insulation is not proportional to the weighted normalized loudness level difference, which is in line with perception theory. This non-linear dependence indicates that a simple increase of a certain airborne sound insulation value does not automatically lead to the same numerical increase in the subjective assessment of the sound insulation.

The differentiation of different sound samples or signal types is demonstrated in Fig. 5-39, showing that the broadband noise signals spread most and show high values above unity, indicating a better subjective assessment of airborne sound insulation than expected. In contrast, the transient sound signals spread much less than the broadband noise signals but yielded results below unity. This indicates that the airborne sound insulation performs subjectively worse than ideally expected. This is hypothesized for an airborne sound insulation in the presence of music or a music-like signal as the intruding noise. Comparing different spectra (i.e., varying spectral adaptation terms C and C_{tr}) but using the same single R-value, as demonstrated in Fig. 5-41, reveals that a construction can be created using an airborne sound insulation that, in terms of the model interpretation, performs best independent of the type of sound signal applied. This implies, however, that the calculated or theoretically predicted airborne sound insulation is likely to perform as subjectively expected. In turn, this means that the model can only predict the probability to be close to a subjectively assessed result independently of the set "ideal" or hypothetical value for reference. That is, the model does not predict any subjective related judgement such as "good" or "bad" but estimates how close a certain transmission loss is to expected in a subjective manner if the construction has been tested in a laboratory. This relationship can be seen in Figs. 5-23, 5-39, and 5-41, where the area embodying the region for the individual results of the R_w-values are seen. The subjective assessment is a function of the signal and of the airborne sound insulation.

6.4 Summary

This chapter summarized the findings of a literature review and this work's finding that the ratings provided as conventional standards are not suitable for comparing the perceived efficacy of insulation. The discussion sums up three facts: first, sound pressure level must be measured to assess airborne sound insulation; second, this sound reduction index must be evaluated subjectively; and third, the level in the receiving room (level of interest) must be assessed by set criteria.

These three facts certainly share common attributes, but in spirit of this thesis, it is useful to think of them as discrete but related concepts. The evaluation of airborne sound insulation is perhaps the most complex and least understood aspect of building acoustics. It is understood that the expression "*evaluation*" inherently judges "*value*", which means that the recipient is engaging in a process designed to provide information based on a judgment of a given situation. Any evaluation, in general, requires processing of information about the situation in question, while "*situation*" in this context is an umbrella term that takes into account objectives, goals, standards, and procedures. Evaluating airborne sound insulation subjectively, information regarding the appropriateness or validity of construction is obtained for which a reliable measurement or assessment has been made. This means that to choose an appropriate airborne sound insulation, more than just a reading from a sound level meter must be taken into account; a single numerical measurement of airborne sound insulation reveals little or nothing about whether a given material is appropriate for a certain situation. For an accurate assessment of a material's value, subjects must be polled in a reliable and informative way. This polling process is what evaluation, in terms of an assessment of airborne sound insulation, is about. A single numerical value of a certain sound insulation is therefore just data; it is the context of the sound insulation for a particular user's purpose that provides the appropriate criteria for evaluation.

The valuation of airborne sound insulation therefore involves more than a measurement of sound pressure levels on both sides of a partition. Rather, it seems that the evaluation of a material is more dependent on indoor soundscape. This study has shown that types of air-borne sound insulation can be clustered depending on purpose and on expectation. However, it was demonstrated that there is at the moment no evaluation capable of assessing airborne sound insulation in a subjective manner that yields a single numerical rating. Nevertheless, the model discussed herein provides sufficient evidence that clustering enables an assessment of the probability that a certain material will fulfil expectations.

7 CONCLUSIONS

This thesis studied the effects of different sound signals on airborne sound insulation by relating objective and subjective measures. This study began with a hypothesis that an index of sound insulation expressed as a single number rating (such as the weighted sound reduction index) cannot provide a reliable measure of the perceived efficacy of the insulation.

The computed efficacy of airborne sound insulation was investigated, revealing that an objective measure of efficacy is dependent on the type of sound signal. The model correctly depicted the experimentally reported loudest and quietest sound samples as well as individual frequency dips in the airborne sound insulation. The implementation of the model showed that the calculation scheme was able to capture details in the studied frequency range very well. As shown by the comparison of calculated values with experimental results, the difference in weighted normalized loudness level demonstrated a dependence on signal characteristics and on the type of airborne sound insulation.

7.1 Research findings

Following the presentation of the objectives in the introduction, the literature review in Chapter 2 revealed the need for a subjective measure of airborne sound insulation. The inadequacy of conventional methods for describing the relation of airborne sound insulation and subjective assessment was described in Chapter 3.1, while discrepancies in the description of airborne sound insulation were detailed in Chapter 3.2.

The model established and introduced in Chapter 4 has been validated and successfully implemented (Chapter 5), in particular for the exploration of different sound signals (Chapter 5.1) and assessed subjective test signals (Chapter 5.2) as well as in practical case studies in which objective and subjective measurements were conducted (Chapter 5.3).

The calculation scheme allowed the evaluation of sound insulation in a psychoacoustic manner, rather than only by sound pressure level differences (Chapter 5.1.2). The model correctly predicts the experimentally reported loudest and quietest sound samples as well as individual frequency dips in airborne sound insulation (Chapter 5.3.1.1). Measurements made with different sound signals indicate that the perceived sound insulation is dependent on the type of source signal. The model correctly identifies different sound signals and reports a measure of “reliable” or “not reliable” to describe the subjective assessed measure with respect to the predicted value (Chapter 5.3.1.2). Thus, the model describes the probability that a measured or computed value of airborne sound insulation corresponds to the perceived efficacy of the insulation.

This work showed that a sound judged subjectively in relation to a given type of airborne sound insulation cannot be expressed as a single numeric value without considering the sound itself (Chapter 5.2.1) The introduced psychoacoustic measures of loudness level and specific fluctuation strength cover important dimensions involved in the noise evaluation process. In general, psychoacoustics describes sound perception with several parameters, including introduced loudness and fluctuation strength (Chapter 5.1.2).

This research showed that the loudness level difference does not adequately distinguish between certain signal characteristics and types (Chapter 5.3.1.3.1). However, introducing specific fluctuation strength into the model yielded results that clearly exposed the signal characteristics of the filter function (i.e., the frequency-dependent airborne sound insulation). In addition, the type of signal was differentiated, which had not been possible for simple level differences. The experimental results showed that for equal sound pressure levels, white noise was perceived to be significantly quieter compared with the other sound samples (Chapter 5.2.2). Furthermore, the experiments showed that, in general, noise samples (i.e., white noise and pink noise) are judged to be perceived quieter than music sound samples, resulting in lower specific fluctuation strength values. Conversely, non-steady-state signals yielded the greatest specific fluctuation strength values and were judged to be perceived louder than the broadband noise samples. The model correctly depicts the experimentally determined loudest and quietest sound samples as well as the individual frequency dips in airborne sound insulation (Chapter 5.3.2.2). The implementation of the model proved that the calculation scheme is able to capture details of the frequency range as well as single numerical values. As shown by the comparison of calculated values with experimental results, the difference in weighted normalized loudness level demonstrates a dependence on signal characteristics and airborne sound insulation (Chapter 5.3.2.1). Thus, this model links the objective and subjective evaluation of airborne sound insulation.

However, it is clear from comparing the psychoacoustic values of loudness level and specific fluctuation strength that no linear relation exists for a specific sound sample. This means that no single number value can be modelled at this time in relation to a certain construction. The main reason for this is that the sound signal (i.e., the type of signal) plays a major part in the perception of the psychoacoustic value of a sound sample, although, as was shown in this research, a construction for a particular sound signal and sound insulation can be found (Chapter 5.3.2.1).

This approach could be a useful tool for investigating airborne sound insulation materials with identical single number ratings but different spectra. As such, this model is intended to be a link between the objective and subjective evaluation of airborne sound insulation.

The most practical question, however, is which airborne sound insulation spectrum results in the best sound insulation to prevent annoyance or disturbance. This determination depends on further investigations in the field and on subjective assessment tests.

This work showed that a sound pressure level difference does not differentiate between different sound signals. This finding led to the conclusion that a measure based on transmission loss is not suitable to predict the related subjective measure (Chapter 6.3). It was further shown that conventional standards are not related to the spectrum of the signal. This finding indicated that a single numerical value describing airborne sound insulation is not correlated with the respective subjective measure. It was demonstrated that the introduced model correctly depicts a frequency dip in the airborne sound insulation curve. Furthermore, it was shown that the model correctly distinguishes between different sound signals, which was also confirmed by subjective tests.

Summarizing the findings of this work it follows that:

- Airborne sound insulation as a single value cannot be represented as a subjective measure
- Airborne sound insulation assessed subjectively is depending on the type of source signal
- The loudness based model depicts the event of a frequency dip correctly
- The loudness based model differentiates correctly between different sound signal types
- The loudness based model describes a probability of how close the result is to an idealized, theoretical, unbiased, or calculated reference value

7.2 Recommendations for future design

The overarching aim of this work was to investigate the performance gap for airborne sound insulation in buildings. Common reasons for separating partition acting weaker in sound protection than expected have long been documented.

However, the performance of a building in an acoustical sense is not only a matter of acoustical technology. It is important to have a good understanding of what buildings will need and ensure that they operate within that purpose for a variety of reasons, such as healthy living conditions, good working conditions, use restrictions, demand forecasting and affordability. The chain of decisions made in the building process is complex and an improved understanding of its structure may help the industry to close the gap between an objective and subjective measure.

Much of the existing literature surrounding this subject calls for more evidence of in-use building performance to build up knowledge of good and poor practice to inform future building design. This evidence should be linked back to design predictions or models. Sound insulation is no longer a kind of "anchor technology". The range of performance options of new materials is enlarged, and approved the combination of various fulfilment options. The aspect of a building’s individual noise protection is recorded for the first time in the reviews, to establish a connection between the building-related need for airborne sound insulation and a subjective overall view of the building.

Hence this piece of work has sought to relate the results of measured, predicted and subjectively assessed airborne sound insulation.

The overall project aim has been addressed through the following objectives:

The largest uncertainty at the design stage is how the building is built: the original airborne sound insulation predictions appear realistic, with the main variation from these due to the way the building is used.

This work has also shown that using default values could result in an overestimation of airborne sound insulation. Considerations of how well a building is likely to be managed for acoustic needs may help determine whether settings for improved constructions should be comparable to the default settings or are likely to be higher.

Further evidence from more buildings is required to gain a better picture of such variables that occur once occupied, which when linked back to the design stage airborne sound insulation predictions, provide more depth to the scenario. The person who builds and runs the prediction or simulation needs deeper insight for likely operation details. It follows that the value of making achievable predictions and understanding realistic operational needs at the design stage, then following through with them once occupied, should be communicated to clients. In reality it may be the case that the person who builds the model is not part of the core design team because the work is outsourced to a different team. More importance needs to be placed on the decision process behind selecting the inputs to this model. For example, despite use of general regulations there is still a significantly higher expectation than is usually considered in design predictions. Attention to more realistic "needs" at the design stage (rather than using regulations) may be necessary to move towards closing the gap. The process of evaluating the uncertainty must be continuous, especially of new building elements and building techniques. New measurement methods as well as new prediction method are needed. The thesis advises future research that could help to optimize the building constructions.

7.3 Future Work

This section describes work that expands on both the study presented and the conclusion drawn from it.

Evidence Based Design

In order to make better design stage predictions, more evidence is needed of what is and is not working in practice. This is an important issue since e.g. thermal and acoustic insulation performances are often contradictory. This would enable a better understanding of likely in-use outcomes of design decisions. It is likely that this is a result of time and resources pressured design projects, which do not place high priority on interrogation of what is really needed from a building, how will it be used and what did not work well in the past. Further to the sound protection issues discussed in this research, occupant satisfaction and productivity are further benefits to this process. More data based around key performance indicators such as occupant density, location of the building, background noise level are needed for a range of building types. Design considerations can then be referenced to how previous building are performing once occupied, in line with parameters that can be measured once the building is occupied, and fed back into the information channel. This information, once collected through further, better directed, post occupancy evaluation studies with well thought out and specified outcomes could be used to place more importance on this part of the design process.

This work extends to more evidence needed on inclusion of sound insulation in projects. As highlighted through this work, very little evidence of measured performance of real construction in terms of psychoacoustic parameters currently exists. The measured performance should be complemented by calculation of the value that each intervention and airborne sound insulation provides to buildings (i.e. financial payback through quality considerations), which would provide valuable information for future project decisions and a measured view of inclusion of such demands.

Up-to-date and Useful Benchmarks

This requires a large survey of satisfaction in buildings, per type of inhabitants. As a starting point, data could be collected before and during occupancies. Further work to establish the value of these metrics, and how this could potentially better link with what inhabitants want to have in their homes would be valuable in order to assist the aim of create a quieter living environment.

Building Performance Evaluation Methodology

Proposed is a review of current building performances evaluation methodology. The latest study reports could be used along with a wider review of what is working and what is not in in an objective manner identifying useful and applicable outcomes form these studies. How this process can be improved and standardised can then be considered. This study has identified strengths and weakness in the prediction of an assessment process. The effectiveness of the COST actions considering airborne sound insulation and environmental issues as well as the LARES (WHO) survey should also be brought into question here.

REFERENCES

Aarts, R. M. (**1992**). A Comparison of Some Loudness Measures for Loudspeaker Listening Tests. *Journal of the Audio Engineering Society*, **40** (3), 142-146.

ABCB, (**2004**). Sound Insulation 2004 – Handbook. Sound Insulation in Buildings, The Australian Building Codes Board (ABCB), The Guideline Document on Sound Insulation in Buildings, http://www.abcb.gov.au/education-events-resources/publications/abcb-handbooks.aspx.

Andrade, C., González, J., Machimbarrena, M., Herráez, M. (**2005**). Validation of EN 12354-1 prediction models by means of Intensity and Vibration measurement techniques in Spanish buildings involving flanking airborne sound transmission. Proceedings of the 4th European Congress on Acoustics (Forum Acusticum), Budapest, Hungary, 2353-2358.

ANSI S1.4 (**1983**). American National Standard: Specification for Sound Level Meters, American National Standards Institute, Acoustical Society of America, Melville NY, USA.

ANSI S3.4 (**2007**). American National Standard: Procedure for the Computation of Loudness of Steady Sounds, American National Standards Institute, Acoustical Society of America, Melville NY, USA.

ASTM E90-92 (**2009**). Standard Test Method for Laboratory Measurement of Airborne Sound Transmission Loss of Building Partitions and Elements, ASTM International, West Conshohocken, PA, USA.

ASTM E336 (**2010**). Standard Test Method for Measurement of Airborne Sound Attenuation Between Rooms in Buildings. ASTM International, West Conshohocken, PA, USA.

ASTM E413 (**2010**). Classification for Rating Sound Insulation, Am. Soc. For Testing and Materials, ASTM International: West Conshohocken, PA, USA.

Aures, W. (**1985**). Ein Berechnungsverfahren der Rauigkeit. (A calculation method of the roughness), (in German), *Acustica*, **58** (5), 268-281.

Ballagh, K.O. (**2004**). Accuracy of Prediction Methods for Sound Transmission Loss. Proceedings of the 33rd International Congress and Exposition on Noise Control Engineering (InterNoise), Prague, Czech Republic, 1-8.

Barlindhaug, R. & Ruud, M. E. (**2008**). “Beboernes tilfredshet med nybygde boliger” (Resident satisfaction with newly built homes). Norsk institutt for by-og regionforskning. NIBR-rapport 2008:14, Oslo, Norway.

Bauer, J. W., and Jean-Paul Vian, J.P. (**1981**). Subjective assessment of sound transmission through party walls. *Journal of the Acoustical Society of America*, **69**, Suppl. 1, (Meeting Abstracts), 47.

Beranek, L.L., Ver, I.L., (**1992**). *Noise and Vibration Control Engineering – Principles and applications*; J. Wiley and Sons, New York 1992, ISBN 0-471-61751-2.

Berger, R. (**1911**). Über die Schalldurchlässigkeit. (About the sound transmission), (in German), Dissertation (doctoral thesis), Technische Hochschule München, Germany.

Berglund, B., Berglund, U., and Lindvall, T. (**1976**). Scaling loudness, noisiness, and annoyance of community noises. *Journal of the Acoustical Society of America*, **60** (5), 1119-1125.

Berglund, B., and Lindvall, T. (**1995**). *Community Noise*. Centre for Sensory Research, Stockholm, Sweden, ISBN 91-887-8402-9.

Bies, D.A., Hansen, C.H. (**2003**). *Engineering Noise Control*, Spon Press, London, UK.

Bodden, M. (**2004**). Sound Quality: from customer expectation to engineering metrics. Proceedings of the 51st Open Seminar on Acoustics (OSA), Gdansk-Sobieszewo, Poland.

Bodlund, K. and Eslon, L. (**1983**). "A survey of the noise climate in some modern Swedish dwellings. Subjective and objective data for 8 residential blocks and 350 flats", SP Report 1983:37, National Testing Institute 1983 (In Swedish).

Boullet, I. (**2005**). La sonie des sons impulsionnels: Perception, Mesures et Modèles. (The loudness of impulsive sounds: perception, measures and models). Thèse de doctorat de l'Université Aix Marseille II, spècialitè Mècanique, option Acoustique. (French). The taken summary is available at: http://genesis-acoustics.com/en/loudness_online-32.html (dated last accessed 28/12/2014).

Bradley, J.S. (**1983**). Subjective Rating of Party Walls, *Canadian Acoustics*, **11** (4), 37-45.

Bradley, J. S. (**2001**). Deriving Acceptable Values For Party Walls Sound Insulation From Survey Results. Proceedings of the 30th International Congress and Exposition on Noise Control Engineering (InterNoise), The Hague, The Netherlands.

Brambilla, G., Carletti, E., and Pedrielli, F. (**2001**). Perspective of the sound quality approach applied to noise control in earth moving machines, *International Journal of Acoustics and Vibration*, **6**, 90-96.

BRE Environment. (**2002**). The 1999/2000 National Survey of Attitudes to Environmental Noise – Volume 3 United Kingdom Results. The building research establishment (BRE). BRE Environment Garston Watford UK.

B&K, (**2014**). Brüel & Kjær. Sound Sources for Building Acoustics: OmniPower™ Sound Source, Data sheet is available at: http://www.ee.bgu.ac.il/~acl/Equip/OMNI.pdf, (dated last accessed 28/12/2014).

BS. CP 111. (**1948**). Structural recommendations for load-bearing walls. British Standards Institution. London.

Buckingham, A. and Saunders, P. (**2009**). *The Survey Methods Workbook: From Design to Analysis*. Polity Press Ltd. Campridge UK.

Buckingham, E. (**1929**). Theory and interpretation of experiments on the transmission of sound through partition walls. Nat'l Bur. Stand. Sci. Papers 20, 194-199.

Carvalho, A. P. O., Faria, J. A. (**1998**). Acoustic Regulations in European Union Countries. Proceedings of the Conference in Building Acoustics "Acoustic Performance of Medium-Rise Timber Buildings", December 3-4, 1998. Dublin, Ireland.

Clark, D. M. (**1970**). Subjective study of the sound-transmission class system for rating building partitions. *Journal of the Acoustical Society of America*, **47** (3), 676-682.

Cole, R. J., and Lorch, R. (**2003**). Buildings, Culture & Environment – informing local & global practices. Blackwell Publishing Ltd, Oxford. UK.

Cooper, I. (**1982**). Comfort theory and practice: barriers to the conservation of energy by building occupants. *Applied Energy*, **11**, 243–288.

COST Action TU0901. (**2013**): "Integrating and Harmonizing Sound Insulation Aspects in Sustainable Urban Housing Constructions". (www.cost.eu/COST_Actions/tud/Actions/TU0901).

Council Directive 89/106/EEC. (**1989**). Council Directive 89/106/EEC on the approximation of laws, regulations and administrative provisions of the Member States relating to construction products, Council of the European Communities. Official Journal of the European Communities. No L 40 / 12. 11 . 2 . 89.

Craik, R. J. M. & Evans, D. I. (**1986**). Workmanship and its effect on sound transmission. Proceedings of the Institute of Acoustics, 8, UK, 463–466.

Craik, R. J. M., Steel JA. (**1989**). The Effect of Workmanship on Sound Transmission through Buildings: Part 1, Airborne Sound. *Journal of Applied Acoustics*, **27** (1), 57-63.

Cremer, L. (**1942**). Theorie der Luftschalldämmung dünner Wände bei schrägem Einfall. (Theory of airborne sound insulation of thinner walls at oblique incidence), (in German). *Akustische Zeitschrift*, **7** (3), 81-104.

Cremer, L. (**1953**). Calculation of sound propagation in structures. *Acustica*, **3** (5), 317-335 (19).

Cremer, L., Heckl, M. (**1996**). *Körperschall - Physikalische Grundlagen und technische Anwendungen*. (Structure-Borne-Sound), (in German). Springer Verlag, Berlin, 2. neu bearb. Auflage, ISBN 3-540-54631-6.

Daniel, P., Weber, R. (**1997**). Psychoacoustical roughness: implementation of an optimized model, *Acta Acustica united with Acustica*, **83**, 113-123.

Dämmig, P., Fischer, H.-W.(**1978**). Untersuchungen über die Abhängigkeit bauakustischer Messungen von der Art des verwendeten Lautsprechers. (Investigation into the Dependence of Building Acoustic Measurements on the Kind of Loudspeaker Used), (in German). *Acta Acustica united with Acustica*, **40** (2), 73-80 (8).

Davis, A. H. (**1925**). Reverberation equations for two adjacent rooms connected by an incompletely soundproof partition, Phil. Mag. 6 (50), 75-80.

defra. (**2006**). Neighbourhood Noise Policies and Practice for Local Authorities – a Management Guide. The Chartered Institute of Environmental Health (CIEH). London. Department for Environment, Food and Rural Affairs (defra). September 2006.

DIN 4110. (**1938**). DIN 4110:1938. Technische Bestimmung für die Zulassung neuer Bauweisen. (Technical specification for the approval of new construction methods), (in German). Beuth Verlag, Berlin, Germany.

DIN 45631. (**2010**). DIN 45631/A1:2010-03. Berechnung des Lautstärkepegels und der Lautheit aus dem Geräuschspektrum - Verfahren nach E. Zwicker – Änderung 1: Berechnung der Lautheit zeitvarianter Geräusche), (Calculation of loudness level and loudness from the sound spectrum - Zwicker method - Amendment 1: Calculation of the loudness of time-variant sound). (in German). Beuth Verlag, Berlin, Germany.

DIN 45692 (**2009**). DIN 45692:2009-08. Messtechnische Simulation der Hörempfindung Schärfe, (Measurement technique for the simulation of the auditory sensation of sharpness), (in German). Beuth Verlag Berlin Germany.

Drucksache. (**1999**). Drucksache 14-2300. Sondergutachten des Rates von Sachverständigen für Umweltfragen. Umweltbedingte Lärmwirkungen 1999. (Special report of the Council of experts for environmental issues. Environmental noise effects 1999), (in German). Bundesministeriums für Umwelt, Naturschutz und Reaktorsicherheit. Deutscher Bundestag – 14. Wahlperiode.

Duvvuru, S., and Erickson, M. (**2013**). The effect of change in spectral slope and formant frequencies on the perception of loudness. *Journal of Voice.* **27**, 691-697.

Eargle, J. M., Foreman, C. (**2015**). *JBL Audio Engineering for Sound Reinforcement*. Publisher: JBL Pro Audio Publications. Hal Leonard Corporation.

enHealth report (**2004**). "The health effects of environmental noise – other than hearing loss.", Department of Health and Ageing. ISBN 0 642 82304 9, Publication approval number 3311 (JN 7845), http://enhealth.nphp.gov.au/council/pubs/pubs.htm.

EN ISO 10052. (**2010**). EN ISO 10052: Acoustics - Field measurements of airborne and impact sound insulation and of service equipment sound (Survey method). European Committee for Standardization (CEN), Brussels, Belgium.

EN 12354-1. (**2000**). EN 12354-1: Building acoustics. Estimation of acoustic performance in buildings from the performance of elements (Part 1: Airborne sound insulation between rooms). European Committee for Standardization (CEN), Brussels, Belgium.

EPA. (**2007**). NOISE SURVEYS 2007. Publication 1169 October 2007, http://www.epa.vic.gov.au/~/media/Publications/1169.pdf.

Esteban, A., Fuente, M., Arribillaga. O., Garcia-Borreguero, I. (**2005**). Accuracy of prediction models applied to Spanish buildings. Proceedings of the 4th European Congress on Acoustics (Forum Acusticum), Budapest, Hungary.

Fahy, F.J. (**1987**). *Sound and Structural Vibration*. Academic Press, London, UK.

Fahy, F., Gardonio, P. (**2007**). *Sound and Structural Vibration*. Academic Press, London, UK.

Fasold, W. (**1959**). Untersuchung zum zweckmäßigsten Sollkurvenverlauf für den Schallschutz im Wohnungsbau. (Study on the appropriate reference curve for the sound insulation in house building), (in German). Proceedings of the 3rd International Congress on Acoustics, Stuttgart, Germany, 1038-1041.

Fasold, W.(**1965**). "Untersuchungen über den Verlauf der Sollkurve für den Trittschallschutz im Wohnungsbau", (Studies on the target curve for impact sound insulation in residential construction), (in German). Mitteilung aus dem Institut für Elektro- und Bauakustik der Technischen Universität, Dresden. *Acustica*, **15**, 271-284.

Fasold, W., Sonntag, E., Winkler, H. (**1987**). *Bau- und Raumakustik. Bauphysikalische Entwurfslehre*. (Building- and room acoustics. Building physics design teaching), (in German). Rudolf Müller Verlag, Köln, Germany.

Fastl, H. (**1985**). Loudness and annoyance of sounds: subjective evaluation and data from I-SO 532 B. Proceedings of the 14th International Congress and Exposition on Noise Control Engineering (InterNoise), Munich, Germany, 1403-1406.

Fastl, H. (**1997**). The Psychoacoustics of Sound-Quality Evaluation. *ACUSTICA acta acustica*. **83**, 754-764.

Fastl, H. (**2006**). Psychoacoustic Basis of Sound Quality Evaluation and Sound Engineering. Proceedings of the 13th International Congress on Sound and Vibration (ICSV), Vienna, Austria.

Fastl, H., Menzel, D., Maier, W. (**2006**). Entwicklung und Verifikation eines Lautheits-Thermometers. (Development and verification of a loudness thermometer), (in German), Proceedings in Fortschritte der Akustik, DAGA 2006, Braunschweig, Germany.

Fastl, H., Völk, F., Straubinger, M. (**2009**). Standards for calculating loudness of stationary or time-varying sounds. Proceedings of the 38th International Congress and Exposition on Noise Control Engineering (InterNoise), Ottawa, Canada.

Fausti, P., Pompoli, R., Smith, R. S. (**1999**). An Intercomparison of Laboratory Measurements of Airborne Sound Insulation of Lightweight Plasterboard Walls. *Journal of Building Acoustics*, **6** (2), 127-140.

Fothergill, L. C. (**1980**). “Recommendations for the measurement of sound insulation between dwellings”, *Applied Acoustics*, **13**, 171-187.

Fothergill, L. C. (**1988**). Sound Insulation between Dwellings. *Journal of Applied Acoustics*, **24**, 321-334.

Furrer, W. and Lauber, A. (**1972**). *Raum- und Bauakustik – Lärmabwehr*. (Room and Building Acoustics – Noise Protection), (in German). 3rd Ed. Birkäuser Verlag Basel und Stuttgart, Germany, 197-230.

Fyhri, A., Aasvang, G.M. (**2010**). Noise, sleep and poor health: Modelling the relationship between road traffic noise and cardiovascular problems. *Science of the Total Environment*, 408, 4935-4942.

Gade, A., Ch. (**2013**). Subjective and objective measures of relevance for the description of acoustics conditions on orchestra stages. International Symposium on Room Acoustics (ISRA), Toronto, Canada, 1-9.

Garg, N., Kumar, A., Maji, S. (**2013**). Practical Concerns Associated with Single-Number Ratings in Measuring Sound Transmission Loss Properties of Partition Panels, *Archives of Acoustics*, **38** (1), 115–124.

Genesis. (**2014)**. Loudness online, available at http://genesis-acoustics.com/en/loudness_online-32.html (dated last accessed 28/12/2014).

Genuit, K., Fiebig, A. (**2005**). Prediction of psychoacoustic parameters. Proceedings of the 2005 National Conference on Noise Control Engineering (Noise-Con), Minneapolis, Minnesota, USA.

Gerretsen, E. (**1994**). European developments in prediction models for buildings acoustics. *Acta Acustica*, **2**, 205-214.

Gerretsen, E. (**2003**), Prediction of sound insulation in buildings: a tool to improve the acoustic quality, Proceedings of Fortschritte der Akustik, DAGA 2003, Plenarvortrag, Munich, Germany, 13-18.

Glasberg, B.R., Moore, B.C.J. (**2002**), A Model of Loudness Applicable to Time-Varying Sounds, *Journal of the Audio Engineering Society*, **50** (5), 331-342.

Green, E. (**2014**). Introduction to Sensation and Perception. Chapter 3 / Lesson 1, available at http://study.com/academy/lesson/intro-to-sensation-and-perception.html (dated last accessed 28/12/2014).

Grimwood, C. (**1997**). Complaints about poor sound insulation between dwellings in England and Wales. *Journal of Applied Acoustics*, **52** (3/4), 211-223.

Grimwood, C.J. , Skinner, C.J. , Raw, G.J. (**2002**). The 1999/2000 National Survey of Attitudes to Environmental Noise. Building Research Establishment, 2001. Noise Forum Conference 20 May 2002.

Gösele, K. (**1965**). Zur Bewertung der Schalldämmung von Bauteilen nach Sollkurven. (Evaluation of sound reduction in building structures by means of grading curves), (in German). *Acustica*, **15**, 264-270.

Gösele, K. (**1968**). Zur Luftschalldämmung von einschaligen Trennwänden und Decken. (Airborne sound insulation of single partitions and ceilings), (in German), *Acustica*, **20** (6), 334-342 (9).

Gösele, K., Koch, S. (**1968**). Die Störfähigkeit von Geräuschen verschiedener Frequenzbandbreite. (The annoyance of noise of different frequency bandwidth), (in German), *Acustica*, **20** (6), 324-333 (10).

Gösele, K., (**1990**). Verringerung der Luftschalldämmung von Wänden durch Dickenresonanzen. (Reduction of airborne sound insulation of walls by thickness resonances), (in German). *Bauphysik*, **12**, H.6, 187-191.

Halliwell, R.E., Nightingale, T.R.T., Warnock, A.C.C., and Birta, J.A. (**1998**). "Gypsum Board Walls: Transmission Loss data". National Research Council of Canada, Internal Report No. 761.

Hansen, C. H. (**2010**). *Fundamentals of Acoustics*. University of Adelaide, Australia. Handbook 2010, e-Book. (http://www.who.int/occupational_health/publications/noise1.pdf).

Haseltine, B. (**2012**). "The evolution of the design and construction of masonry buildings in the UK". Proceedings of the 15th International Brick and Block Masonry Conference (IB2MaC), Florianopolis, Brazil.

HEAD Acoustics GmbH. (**2014**). HEAD Acoustics GmbH, Application Note 01-14: "Psychoacoustic Analyses in the ArtemiS SUITE," available at http://head-acoustics.de/downloads/eng/application_notes/Psychoacoustic_Analyses_II_e.pdf (date last accessed 28/12/2014).

Heckl, M. (**1981**). The Tenth Sir Richard Fairey Memorial Lecture: Sound Transmission in Buildings, *Journal of Sound and Vibration*, **77** (2), 165-189.

Heckl, M., Donner, U., (**1985**). Schalldämmung dicker Wände. (in German). *Rundfunktechnische Mitteilungen*, **29**, H.6, 287- 291.

Heckl, M., Müller, H.A. (**1994**). Taschenbuch der Technischen Akustik. (Pocketbook of Technical Acoustics), (in German). Springer Verlag, Berlin, Germany.

Hellman, R., and Zwicker, E. (**1987**). "Why can a decrease in dB(A) produce an increase in loudness?", *Journal of the Acoustical Society of America*, **82** (5), 1700-1705.

Hongisto, V. (**2000**). Airborne sound insulation of wall structures - measurement and prediction methods. Doctoral thesis, Helsinki University of Technology, Laboratory of Acoustics and Audio Signal Processing, Report 56, 2000, Espoo, Finland.

Hongisto, V., Oliva, D., Keränen, J. (**2014**). Subjective and Objective Rating of Airborne Sound Insulation – Living Sounds. *Acta Acustica united with Acustica*, **100** (5), 848-863.

Hongisto, V., Mäkiläb, M., Suokasa, M. (**2015**). Satisfaction with sound insulation in residential dwellings – The effect of wall construction. *Building and Environment*, **85**, 309–320.

Hveem, S. (**2010**). "Unngå byggskader – Lydisolasjonskvalitet i boliger" (Avoid building faults – Sound insulation quality in dwellings). SINTEF Byggforsk, 2010. http://www.sintef.no/upload/Artikkel-05-10-ByggAktuelt.pdf. Note: This article summarizes main findings about sound insulation from (Barlindhaug, 2008).

IEC 61672 (**2013**). IEC 61672-1:2013. Electroacoustics - Sound level meters - Part 1: Specifications. International Electrotechnical Commission. ISBN 978-2-8322-1087-1

I-INCE (**2009**). I-INCE PUBLICATION: 09-1. Survey of Legislation, Regulations, and Guidelines for Control of Community Noise. Final Report of I-INCE Technical Study Group on Noise Policies and Regulations (TSG 3). International Institute of Noise Control Engineering.

INSUL (**2014**). Software Tool, "Insul v. 8.0.0", Marshall Day Acoustics Ltd Pty, Auckland, New Zealand, (http://www.insul.co.nz/).

ISO. (**1974**). Technical Report 3352. Acoustics - Assessment of noise with respect to its effect on the intelligibility of speech. Genève, Switzerland: International Organization for Standardization.

ISO 140-2. (**1991**). Acoustics; measurement of sound insulation in buildings and of building elements; part 2: determination, verification and application of precision data. (This standard has been revised by: ISO 12999-1:2014).

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. (This standard has been revised by: ISO 16283-1:2014).

ISO 226. (**2003**). ISO 226: Acoustics - Normal equal-loudness-level contours. Genève, Switzerland: International Organization for Standardization.

ISO 532/R. (**1975**). ISO 532/R: Acoustics- Method for Calculating Loudness Level. (Standard confirmed in 2012). Genève, Switzerland: International Organization for Standardization.

ISO/R 717. (**1968**). International Standards Organisation Recommendation, ISO 717/R: Acoustics - Rating of sound insulation for dwellings. Genève, Switzerland: International Organization for Standardization.

ISO 717-1. (**2013**). ISO 717-1: Acoustics – Rating of sound insulation in buildings and of building elements (Part 1: Airborne sound insulation). Genève, Switzerland: International Organization for Standardization.

ISO 10140-2. (**2010**). Acoustics - Laboratory measurement of sound insulation of building elements – Part 2: Measurement of airborne sound insulation. Genève, Switzerland: International Organization for Standardization.

ISO 10140-4. (**2010**). Acoustics - Laboratory measurement of sound insulation of building elements – Part 4: Measurement procedures and requirements. Genève, Switzerland: International Organization for Standardization.

ISO 12001. (**1996**). ISO 12001: Acoustics - Noise emitted by machinery and equipment - Rules for the drafting and presentation of a noise test code. Genève, Switzerland: International Organization for Standardization.

ISO 15186-2. (**2003**). Acoustics - Measurement of sound insulation in buildings and of building elements using sound intensity - Part 2: Field measurements. Genève, Switzerland: International Organization for Standardization.

ISO 15712-1. (**2005**). Building acoustics - Estimation of acoustic performance of buildings from the performance of elements - Part 1: Airborne sound insulation between rooms. Genève, Switzerland: International Organization for Standardization.

ISO 16283-1. (**2014**). ISO 16283-1: Acoustics - Field measurement of sound insulation in buildings and of building elements - Part 1: Airborne sound insulation. Genève, Switzerland: International Organization for Standardization.

ISO/NP 16717-1. (**2012**). ISO/NP 16717-1: Acoustics - Evaluation of Sound Insulation Spectra by Single-Numbers (Part 1: Airborne Sound Insulation, ISOTTC 43/SC2). Genève, Switzerland: International Organization for Standardization.

ISO 18233. (**2006**). Acoustics -- Application of new measurement methods in building and room acoustics. Genève, Switzerland: International Organization for Standardization.

Jeon, J.Y., Ryu, J.K., and Lee, P.J. (**2010**). A quantification model of overall dissatisfaction with indoor noise environments in residential buildings. *Journal of Applied Acoustics,* **71**, 914-921.

Jeon, J.Y., You, J., Jeong, C.I., Kim, S.Y., Jho, M.J. (**2011**). Varying the spectral envelope of air-conditioning sounds to enhance indoor acoustic comfort. *Building and Environment*. **46**, 739-746.

Joiko, K., Bormann, V., Kraak, W. (**2002**). Durchhören von Sprache bei Leichtbauwänden. (Speech intelligibility through prefabricated walls of gypsum plasterboard), (in German), *Zeitschrift Lärmbekämpfung*, **49** (3), 79-85.

Jones, M.R., Fay, R.R., Popper, A.N. (**2010**). *Music Perception*. Springer-Verlag New York Dordrecht Heidelberg London.

Kihlman, T. (**1995**). Residential acoustics--A European perspective, *Journal of The Acoustical Society of America*, **98** (5), 2878.

Kingsbury, B.A. (**1927**). A direct comparison of the loudness of pure tones, Phys. Rev. **29**, 588–600.

Kitamura T, Shimokura R, Sato S, Ando Y. (**2002**). Measurement of Temporal and Spatial Factors of a Flushing Toilet Noise in a Downstairs Bedroom. *Journal of Temporal Design in Architecture and the Environment*, **2** (1), 13-19.

Kranendonk, F., Gerretsen, E., Luxemburg, L.C.J. (van) (**1993**). Akoestische kwaliteit van woningen versus de beleving van burengeluid. (Acoustic quality homes versus the experience of neighbors sound), (in Dutch). TNO-BOUW, TUE-Bouwkunde; 93-CBO-R3185.

Kropp, W., Pietrzyk, A., and Kihlman, T. (**1994**). On the meaning of the sound reduction index at low frequencies. *Acta Acustica*, **2**, 379-392.

Kortchmar, L., Vorländer, M., Slama, J. (**2001**). Sound quality evaluation for the workplace: Research on the influence of spatial sound distributions. *Acta Acustica united with Acustica*, **87**, 495-499.

Kuerer, R. C. (**1997**). Classes of acoustical comfort in housing: Improved information about noise control in buildings. *Applied Acoustics*, **52** (3/4), 197-210.

Kuwano, S., et al (**1989**). Advantages and Disadvantages of A-weighted Sound Pressure Level in Relation to Subjective Impression of Environmental Noises. *Noise Control Engineering Journal*, **33** (3), 107-115.

Lang, J. (**1997**). A round robin on sound insulation in buildings. *Applied Acoustics*, **52** (3/4), 225-238.

Lang, J., Pierrard, R., Schönbäck, W. (**2006**). Schallschutz im Wohnungsbau. (Sound protection housing), Endbericht. (in German), Fachbereich Finanzwissenschaft und Infrastrukturpolitik (IFIP), Vienna, Austria. (http://www.ifip.tuwien.ac.at/forschung/SCHALL/SCHALL_End-bericht.pdf).

Lang, J. (**2007**). Schallschutz im Wohnungsbau. (Sound protection in housing), (in German), *Zeitschrift wksb*, **59**, 5-19.

Langdon, F. J., Buller, I.B., and Scholes, W.E. (**1981**). "Noise from neighbours and the sound insulation of party walls in houses." *Journal of Sound and Vibration*, **79** (2), 205-228.

Lawless, H. T., Heymann, H. (**2010**). *Sensory Evaluation of Food*, Food Science Text Series, Springer Science + Business Media, LLC 2010, Chapter 6: Measurement of Sensory Thresholds, 125-147.

Lawrence, A. B. (**1969**). Rating Systems for the Sound Insulation of Building Elements. Proceedings of the 1969 Conference of the Australian Acoustical Society (A.A.S.), Noise reduction of Floors, Walls, and Ceilings. Hotel Florida, Terrigal, 11th, 12th October 1969, Paper A.

Le Jeannic, T., Vidalenc, J. (**2005**). Environnement, nuisances et insécurité: Indicateurs sociaux 1996-2004. (Environment, nuisance and insecurity: social indicators 1996-2004.), (in French). Insee Résultats-Societé, No **45**, Décembre 2005. 1-48. (http://www.youscribe.com/catalogue/etudes-et-statistiques/savoirs/sciences-humaines-et-sociales/environnement-nuisances-et-insecurite-indicateurs-sociaux-1960097).

Lee, P.J., Shim, M.H., and Jeon, J.Y. (**2010**). Effects of different noise combinations on sleep as assessed by a general questionnaire. *Journal of Applied Acoustics,* **71**, 870-875.

Leissa, A.W. (**1969**). Vibration of Plates. NASA Sp-160. Office of Technology Utilization, National Aeronautics and Space Administration, Washington , D.C.

Leppington, F.G., (**1996**). Acoustic radiation from plates into a wedge-shaped fluid region: Application to the free plate problem. Proc. Royal Soc. London A, **452**, 1745ff.

Leventhall, H.G. (**2004**). Low frequency noise and annoyance. *Noise and Health*, **6**, 59-72.

Ljunggren, S. (**1991**). "Airborne Sound Insulation of Thick Walls", *Journal of the Acoustical Society of America*, **89** (5), 2338-2345.

Ljunggren, F., Ågren, A. (**2012**). How to match building acoustic measurements with subjective judgements? Proceedings of the 41st International Congress and Exposition on Noise Control Engineering (InterNoise), New York City, USA.

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

London, A. (**1949**).Transmission of Reverberant Sound through Single Walls. *Journal of the Research National Bureau of Standard,* **42**, 605, RP1998.

London, A. (**1950**).Transmission of Reverberant Sound through Double Walls. *Journal of the Acoustical Society of America*, **22** (2), 270-279.

Lord Rayleigh (**1877**). *Theory of Sound*. Macmillan Company, London.

Lorenz, A. M. (**2000**). Klangalltag – Alltagsklang. Evaluation der Schweizer Klanglandschaft anhand einer Repräsentativbefragung bei der Bevölkerung. (Sound life - everyday sound. Evaluation of the Swiss landscape of sound based on a representative survey of the population.), (in German), Zentralstelle der Studentenschaft, Zürich, 2000. (Summary: Zeitschrift, tec21, **48**/2001, Zürich, Schweiz, 24-26.)

Lowry, S. (**1989**). Housing and Health - Noise, space, and light. *British Medical Journal* (BMJ), **299**, 1493-1442.

Mahn, J., and Pearse, J. (**2012**). The Uncertainty of the Proposed Single Number Ratings for Airborne Sound Insulation. *Journal of Building Acoustics*, **19**, 145-172.

Maidanik, G., (**1962**). Response of ribbed panels to reverberant acoustic fields. *Journal of the Acoustical Society of America*, **34**(6), 809-826.

Masovic, D.B., Pavlovic, D.S., and Mijic, M.M. (**2013**). On the suitability of ISO 16717-1 reference spectra for rating airborne sound insulation. JASA EL 420, *Journal of the Acoustical Society of America,* **134**.

McMinn, T. (**2013**). "A-Weighting": Is it the metric you think it is?, Proceedings of Acoustics 2013, Victor, Harbor, Australia.

Mirowska, M. (**2004**). Evaluation of the low frequency noise in dwellings – its scale of annoyance. Proceedings of the 51st Open Seminar on Acoustics (OSA), Gdansk-Sobieszewo, Poland.

Moore, B.C.J., Glasberg, B.R., Baer, T. (**1997**). A Model for the Prediction of Thresholds, Loudness, and Partial Loudness, *Journal of the Audio Engineering Society*, **45** (4), 224-240.

Moore, B.C.J. (**2004**). *An Introduction to the Psychology of Hearing*, 5th Edition, Elsevier Academic Press, London.

Mortensen, F.R. (**1999**). Subjective evaluation of noise from neighbours - with focus on low frequencies. Publication no 53, Main Project, Technical University of Denmark, Department of Acoustic Technology.

Müller, S., Massarani, P. (**2001**). Transfer-Function Measurement with Sweeps, *Journal of the Audio Engineering Society*, **49**, 443-471.

Müllner H., Humer C., Stani M. M. (**2007**). Lightweight Building Elements with Improved Sound Insulation, Considering the Low Frequency Range. Proceedings of the 3rd Congress of the Alps Adria Acoustics Association. 27–28 September 2007, Graz, Austria.

Müllner, H., Frey, A., and Humer, C. (**2008**). Sound insulation properties of building elements, considering the frequency range below 100 Hz. Proceedings of Acoustics ´08, Paris, France, 6025-6030.

Muzet, A. (**2007**). Environmental noise, sleep and health. *Sleep Medicine Reviews*, **11**, 135-142.

Neubauer, R.O. (**2004**). Subjective Estimation of Airborne Sound Insulation in Buildings and How to Quantify the Real Acoustical Comfort of Dwellings. Proceedings of the 51st Open Seminar on Acoustics (OSA), Gdansk-Sobieszewo, Poland.

Neubauer, R. O. (**2005**). “Airborne Sound Insulation in Dwellings and its Subjective Estimation”. Proceedings of the 12th International Congress on Sound and Vibration (ICSV), Lisbon, Portugal.

Neubauer, R.O., Kang, J. (**2011 a**). “What Describes the Airborne Sound Insulation in Technical and Subjective Regard?” Proceedings of the 6th European Congress on Acoustics (Forum Acusticum), Aalborg, Denmark, ISSN 2221-3767, 1783-1787.

Neubauer, R.O., Kang, J. (**2011 b**). Temporal aspects of airborne sound insulation and how it affects the subjective estimation. Proceedings of the 5th International Symposium on Temporal Design, Sheffield, United Kingdom.

Neubauer, R.O., Kang, J. (**2012 a**). Rating Airborne Sound Insulation in Terms of Time Structure of the Signal. Proceedings of the 41st International Congress and Exposition on Noise Control Engineering (InterNoise), New York City, USA.

Neubauer, R.O., Kang, J. (**2012 b**). Time Structure Of The Signal In Airborne Sound Insulation. Proceedings of the 9th European Conference on Noise Control (EuroNoise), Prague, Czech Republic.

Neubauer, R.O., Kang, J. (**2013 a**). Subjective Evaluation of Airborne Sound Insulation below 100 Hz. Proceedings of the Joint Conference on Acoustics, AIA-DAGA 2013, Merano, Italy.

Neubauer, R.O., Kang, J. (**2013 b**). Airborne sound insulation as a measure for noise annoyance. Proceedings of the 21st International Congress on Acoustics (ICA), Montréal, Canada.

Neubauer, R.O., Scamoni, F. (**2013**). Die Akustische Klassifikation in Italien und Deutschland: Perspektiven Und Möglichkeiten. (in German). Proceedings of the Conference on Acoustics EUROREGIO, 22 March 2013, Merano, Italy.

Neubauer, R.O., Kang, J. (**2014 a**). Airborne sound insulation in terms of a loudness model. *Journal of Applied Acoustics*, **85**, 34-45.

Neubauer, R.O., Kang, J. (**2014 b**). Airborne Sound Insulation Based on a Model of Loudness. Proceedings of the 21st International Congress on Sound and Vibration (ICSV), Beijing, China.

Neubauer, R.O., Kang, J. (**2014 c**). A Model Based on Loudness Level to Describe Airborne Sound Insulation. Proceedings of the 43th International Congress and Exposition on Noise Control Engineering (InterNoise), Melbourne, Australia.

Neubauer, R.O. (**2015**). COST Action TU0901 – Harmonisierung von Kennwerten und Klassifikationsschema für den baulichen Schallschutz – Eine Zusammenfassung der Ergebnisse, (Harmonisation of descriptors and classification scheme for the structural sound protection - A summary of the results), (in German). Proceedings in Fortschritte der Akustik, DAGA 2015, Nuremberg, Germany.

Niemann, H., Maschke, C., Hecht, K., Huber, M. (**2005**). "Nachbarschaftslärm bedingte Belästigung und Erkrankungsrisiko - Ergebnisse des Paneuropäischen LARES-Survey", (Neighbourhood noise caused nuisance and disease risk - results of the Pan-European survey of LARES), (in German), Proceedings of Fortschritte der Akustik, DAGA 2005, Munich, Germany.

Niemann, H.; Maschke, C.; Hecht, K. (**2005**). "Lärmbedingte Belästigung und Erkrankungsrisiko Ergebnisse des paneuropäischen LARES-Survey", (Noise-induced annoyance and disease risk results of the Pan-European survey of LARES), (in German), Bundesgesundheitsblatt – Gesundheitsforschung – Gesundheitsschutz, **48** (3), 315 – 328.

Noise (**2013**). Technical Handbooks 2013 Domestic – Noise, The Scottish Government Publications. Section 5 – Noise (http://www.gov.scot/Resource/0045/00459728.pdf)

Norwich, Kenneth H. (**1993**). *Sensation, and Perception*. Academic Press, Inc. A Division of Harcourt Brace & Company San Diego, California, 326.

Northwood, T. D. (**1975**). Criteria for Airborne Sound Insulation between Dwellings. (Summary of paper presented at meeting of Canadian Acoustical Association, 8 October 1975, 2-8.

Ortscheid, J., Wende, H. (**2006**). Lärmbelästigung in Deutschland. Ergebnisse der Befragung im Jahr 2004. (Noise pollution in Germany. Results of the survey in 2004), (in German), Zeitschrift für Lärmbekämpfung, **53** (1), 24-30.

ÖNORM S 5012. (**2012**). ÖNORM S 5012: 2012 04 15, " Schalltechnische Grundlagen für die Errichtung von Gastgewerbebetrieben, vergleichbaren Einrichtungen sowie den damit verbundenen Anlagen - Ermittlung der Emissionen". (Acoustic principles for the construction of restaurants, similar establishments and related installations - Determination of emissions), (in German). Austrian Standards Institute, Vienna, Austria.

Osipov, A., Mees, P., (**1997**). Vermeir, G., Low-Frequency Airborne Sound Transmission through Single Partitions in Buildings. *Applied Acoustics*, **52** (3/4), 273-288.

Park, H.K., Bradley, J.S. (**2009**). Evaluating standard airborne sound insulation measures in terms of annoyance, loudness, and audibility ratings. *Journal of the Acoustical Society of America,* **126**, 208-219.

Park, H. K.; Bradley J. S. and Gover B. N. (**2008**). Evaluating airborne sound insulation in terms of speech intelligibility. *Journal of the Acoustical Society of America*, **123** (3), 1458–1471.

Park, H.K., Bradley, J.S., and Gover, B.N. (**2007**). Using speech intelligibility scores to rate sound insulation. *Canadian Acoustics*, **35**, 122-123.

Parmanen, J. (**2001**). System for Rating of Airborne Sound Insulation in Buildings and of Building Elements. *Acta Acustica united with Acustica,*, **87**, 101-117.

Parmanen, J. (**2007**). A-weighted sound pressure level as a loudness/annoyance indicator for environmental sounds - Could it be improved? *Journal of Applied Acoustics,* **68**, 58-70.

Pickles, J.O. (**2008**). *An Introduction to the Physiology of Hearing*. 3rd Edition, Emerald Group Publishing Limited.

Praščević, M., Cvetković, D., Mihajlov, D. (**2012**). Comparison of Prediction and Measurement Methods for Sound Insulation of Lightweight Partitions. FACTA UNIVERSITATIS, Series: Architecture and Civil Engineering, **10** (2), 155-167.

Pompoli, R. (**1994**). Intercomparison of laboratory measurements of airborne sound insulation of walls. Report on the EUProject MAT1-CT-940054.

Poulsen, T. and Mortensen, F. R. (**2002**). Laboratory Evaluation of Annoyance of Low Frequency Noise, Working Report No. 1 - Arbejdsrapport fra Miljøstyrelsen, Technical University of Denmark, Acoustic Technology, 1-66. http://www.miljoestyrelsen.dk/udgiv/publications/2002/87-7944-955-7/pdf/87-7944-956-5.pdf (date last accessed 20/03/2015).

Quinlan, D. A. (**1994**). A Comparative Study of Zwicker's Method for Calculating the Loudness of Continuous Sounds. *Noise Control Engineering Journal*, **42** (3), 117-126.

Quirt, J. D. (**1982**). "Sound transmission through windows I. Single and double glazing". *Journal of the Acoustical Society of America*, **72** (3), 834–844.

Rademacher, H.-J. (**1955**). Subjektive Bewertung der Schalldämmung, untersucht an elektrisch nachgebildeten Schalldämmkurven. (Subjective evaluation of acoustic insulation, studied electrically imitated sound insulation curves), (in German), *Acustica*, **5** (1), 19-27(9).

Raggam, R.B., et al. (**2007**). Personal noise ranking of road traffic: Subjective estimation versus physiological parameters under laboratory conditions. *International Journal of Hygiene and Environmental Health*, **210**, 97-105.

Rasmussen, B.; Rindel, J.H. (**1996**). Wohnungen für die Zukunft: Das Konzept des akustischen Komforts und welcher Schallschutz von den Bewohnern als zufriedenstellend beurteilt wird. (Homes for the future: The concept of acoustic comfort and which soundproofing is judged by the inhabitants as being satisfactory), (in German). *Zeitschrift wksb*, **41** (38), 4-11.

Rasmussen, B. (**2004**). Sound insulation between dwellings – Classification schemes and building regulations in Europe. Proceedings of the 33rd International Congress on Noise Control Engineering (InterNoise), Prague, Czech Republic.

Rasmussen, B.; Rindel, J.H. (**2005**). Concepts for evaluation of sound insulation of dwellings - from chaos to consensus?, Proceedings of the 4th European Congress on Acoustics (Forum Acusticum), Budapest, Hungary.

Rasmussen, B. & Lang, J. (**2009**). How much protection do the sound insulation standards give and is this enough?. Proceedings of EURONOISE 2009. Action on noise in Europe. 8th European Conference on Noise Control, 26-28 October 2009, Edinburgh International Convention Centre, Edinburgh, United Kingdom.

Rasmussen, B.; Rindel, J.H. (**2010**). Sound insulation between dwellings - Descriptors applied in building regulations in Europe. *Journal of Applied Acoustics,* **71**, 171-180.

Rasmussen, B., (**2010**). "Sound insulation between dwellings – Requirements in building regulations in Europe". *Applied Acoustics*, **71** (4), 373-385.

Rasmussen, B. & Machimbarrena, M. (editors). (**2014**). COST Action TU0901 – Building acoustics throughout Europe. Volume 1: Towards a common framework in building acoustics throughout Europe. (www.cost.eu/COST_Actions/tud/Actions/TU0901).

Raw, G.J., Oseland, N.A. (**1991**). Subjective response to noise through party floors in conversion flats. *Applied Acoustics*, **32**, 215–231.

Rindel, J. H., (**1994**). Dispersion and Absorption of Structure-Borne Sound in Acoustically Thick Plates. *Applied Acoustics*, **41**, 97-111.

Robinson, D.W. (**1953**). The relation between the sone and phon scales of loudness. *Acustica*, **3** (5), 344-358.

Roos, M., Henze, N., Seeber, S., Kurtze, L., Ellermeier, W. (**2011**). Measuring and Scaling the Unpleasantness of PV-Inverter. Sound Emissions based on Psychoacoustic Metrics. Proceedings of the 26th European Photovoltaic Solar Energy Conference and Exhibition.

Ruf, A., Fischer, H.-M. (**2009**). Umsetzung der europäischen Normen des baulichen Schallschutzes für das Bauen mit Gips-Wandbauplatten (Transposition of European standards of structural sound protection for building with gypsum wall boards). Abschlussbericht Nr. 122 005 05 P zum AIF Vorhaben Nr. 14656 N (in German), 1-201.

Ryu, J.K., and Jeon, J.Y. (**2011**). Influence of noise sensitivity on annoyance of indoor and outdoor noises in residential buildings. *Journal of Applied Acoustics,* **72**, 336-340.

Salomons, E.M., and Janssen, S.A. (**2011**). Practical Ranges of Loudness Levels of Various Types of Environmental Noise, Including Traffic Noise, Aircraft Noise, and Industrial Noise. *International Journal of Environmental Research and Public Health*, **8**, 1847-1864.

Scharf, B.; Hellman, R. (**1978**). How Best to Predict Human Response to Noise on the Basis of Acoustic Variables. Proceedings of the 3rd Congress on Noise as a Public Health Problem. Freiburg, Germany. Published in: ASHA Reports Nr. 10, 1980, 475-487.

Scharf, B. (**1978**). *Loudness*. In: Handbook of Perception. **4**, Hearing. Edited by E. C. Carterette and J.C. Morton, Academic Press, New York.

Sharp, B. H., Gurovich, Y. A., Fazeli, F. K., Miller, E. (**2013**). Assessment of Sound Insulation Treatments. Final Report, Prepared for Airport Cooperative Research Program (ACRP), Transportation Research Board of The National Academies, Project No. 02-09, the National Research Council (TRB), U.S.A, 1-77.

Sepmeyer, L. W. (**1986**). Study of the sound transmission class system for rating building partitions: Another view. *Journal of the Acoustical Society of America*, **80** (5), 1404-1407.

Sewell, E. C. (**1970**). Transmission of reverberant sound through a single-leaf partition surrounded by an infinite rigid baffle. *Journal of Sound and Vibration*, **12** (1), 21-32.

Simmons, C. (**2001**). Systematic comparison of sound insulation measured in situ with values calculated according to EN 12354 yields confident data of the acoustical properties of building elements. Proceedings of the 17th International Congress on Acoustics (ICA), Rom, Italy.

Schlittenlacher, J., Hashimoto, T., Fastl, H., Namba, S., Kuwano, S., and Hatano, S. (**2006**). Loudness of pink noise and stationary technical sounds. Proceedings of the 40th International Congress and Exposition on Noise Control Engineering (InterNoise), Osaka, Japan.

Schoch, A. (**1937**). *Die physikalischen und technischen Grundlagen der Schalldämmung im Bauwesen*. (The physical and technical basis of sound insulation in the building industry), (in German). S. Hirzel Verlag Leipzig, Germany.

Schöne, P. (**1979**). Messungen zur Schwankungsstärke von amplitudenmodulierten Sinustönen, (Fluctuation Strength of Amplitude-Modulated Tones), (in German). *Acustica*, **41**, 252-257.

Scholl, W., Lang, J., Wittstock, V. (**2011**). Rating of Sound Insulation at Present and in Future. The Revision of ISO 717. *Acta Acustica united with Acustica*, **97** (4), 686-698.

Shomer, P.D. et al (**2001**). Evaluation of loudness-level weightings for assessing the annoyance of environmental noise. *Journal of the Acoustical Society of America,* **110** (5), 2390-2397.

Smith, S., Mackenzie, R., Mackenzie, R., and Waters-Fuller, T. (**2001**). Housing and Sound Insulation, A Review of Sound Insulation Performance in Scottish Domestic Construction, (Summary). (http://researchrepository.napier.ac.uk/4757/1/Smith2.pdf).

Smith, R. S., Mackenzie, R.K., Mackenzie, R.G., and Waters-Fuller, T. (**2003**). The implications of ISO 717 spectrum adaptation terms for residential dwellings. Proceedings of the Institute of Acoustics **25** (5).

Smith, S., Macdonald, R., Lurcock, D., Mackenzie, R. (**2007**). Airborne sound transmission, ISO 140 and Influence of ISO 717-1 Spectrum Adaptation Terms. Proceedings of the 19th International Congress on Acoustics, Madrid, Spain.

Smith, R. S., Mackenzie, R. (**2014**). Compliance, performance and sound insulation – a decade review of the UK robust approach. Proceedings of the 7th European Congress on Acoustics (Forum Acusticum), Krakow, Poland.

Schmitz, A., Meier, A., Raabe, G. (**1999**) Inter-laboratory test of sound insulation measurements on heavy walls: Part I – Preliminary test. *Building Acoustics*, **6**, 159-169.

Sottek, R., Genuit, K. (**2005**). Models of signal processing in human hearing. *International Journal of Electronics and Communications* (AEÜ), **59**, 157-165.

Sottek, R. (**2014**). Progress in calculating tonality of technical sounds. Proceedings of the 43th International Congress and Exposition on Noise Control Engineering (InterNoise), Melbourne, Australia, 1-9.

Sottek, R., Bray W. (**2015**). Application of a New Perceptually-Accurate Tonality Assessment Method. Proceedings of the SAE 2015 Noise and Vibration Conference and Exhibition. DeVos Place Convention Center, Grand Rapids, Michigan, USA.

St. Pierre, R.L. Jr., Maguire, D.J. (**2004**). The Impact of A-weighting Sound Pressure Level Measurements during the Evaluation of Noise Exposure. Proceedings of the 2004 National Conference on Noise Control Engineering (NOISE-CON), Baltimore, Maryland, USA, 702-708.

Stefaniw, A. (**2001**). Hearing Comfort in Classrooms: How Much Difference Does Design Make. Proceedings of the 141st Meeting of the Acoustical Society of America, Chicago, IL, USA.

Stevens, S. S. (**1955**). "The Measurement of Loudness". *Journal of the Acoustical Society of America,* **27** (5), 815-829.

Stevens S. S. (**1956**). "Calculation of the Loudness of Complex Noise". *Journal of the Acoustical Society of America,* **28** (5), 807-832.

Suzuki, Y., Takeshima, H. (**2004**). Equal-loudness-level contours for pure tones. *Journal of the Acoustical Society of America*, **116** (2), 918–933.

Szudrowicz, B., Izewska, A. (**1995**). Simplified evaluation of flanking transmission based on the mean mass and mean area of flanking elements. *Applied Acoustics*, **46** (3), 307–319.

Tachibana, H., Hamado, Y., and Sato, F. (**1988**). Loudness evaluation of sounds transmitted through walls - Basic experiments with artificial sounds. *Journal of Sound and Vibration,* **127**, 499-506.

Tachibana, H., Lang, W.W., (**2005**). Draft Final Report of I-INCE TSG#3 – Noise Polices and Regulations, Proceedings of the 34th International Congress and Exposition on Noise Control Engineering (InterNoise), Rio de Janeiro, Brazil.

Tadeu, A. J. B., Mateus, D. M. R. (**2001**). Sound transmission through single, double and triple glazing. Experimental evaluation. *Applied Acoustics*, **62** (3), 307–325.

Taibo, L., and Glasserman de Dayan, H.(**1983**). Analysis of variability in laboratory airborne sound insulation determinations. *J. Sound and Vibration*, **91** (3), 319-329.

Tech-Ref-Nr2. (**2015**). Acoustica Products Ltd., UK, http://aco-on.co.uk/assets/Uploads/Data_Sheets_PDF/TECH-REF-NR2.pdf. (date last accessed 15/02/2015).

Terhardt, E. (**1974**). On the perceptions of periodic sound fluctuation (Roughness). *Acustica*, **30** (4), 201-213.

Terhardt E., Stoll G., und Seewann M., (**1982**). „Algorithm for extraction of pitch salience from complex tonal signals“, *Journal of the Acoustical Society of America,* **71** (3), 679–688.

Thaden, R. und Vorländer, M. (**2000**). Hörversuche zum Vergleich unterschiedlicher Bewertungsverfahren für Luftschalldämmmaße. (Hearing tests to compare different evaluation procedures for airborne sound insulation values), (in German). Proceedings of Fortschritte der Akustik, DAGA 2000, Oldenburg, Germany.

The Building Regulation (**2000**). Approved Document E. The Building (Approved Inspectors etc) Regulations 2000. UK Regulation, into force since 1 July 2003.

Timmel, R., (**1991**). Untersuchungen zum Einfluss der Randeinspannung biegeschwingender rechteckiger Platten auf den Abstrahlgrad am Beispiel von geklemmter und gestützter Platte und Untersuchungen zu Streuung des Abstrahlgrades. (Investigations on the effect of edge boundary conditions for flexurally vibrating rectangular panels on the radiation efficiency as exemplified by clamped and simply supported panels), (in German). *Acustica*, **73** (1), 12-20.

Tonin, R., (**2004**). THE BCA 2004 – A PLAN FOR THE FUTURE. Proceedings of Acoustics 2004, Gold Coast, Australia, 141-150.

UBA Wien (**2000**). Umweltbundesamt Wien / Federal Environment Agency Vienna. Begrenzung der Schallemission durch Musikanlagen. (Limitation of the sound emission through sound systems), (in German), Vienna, Austria, BE-168, ISBN 3-85457-472-X.

UBA (**2002**). online-Lärmumfrage des Umweltbundesamtes. (Noise survey of the Federal Environmental Agency), (in German), Bericht Oktober 2002, Umweltbundesamt, Zusammengestellt von Jens Ortscheid. (www.umweltbundesamt.de).

UBA (**2013**). The UBA annual publication 2013. What Matters 2013, Annual Report of the Federal Environment Agency. (www.umweltbundesamt.de).

V 56-2 (**1952**). Zeller, W. and Elsner, H., Messung der Lärmminderung und der Lärmdämmung I, (Measurement of noise reduction and noise insulation), (in German). DK 534.839, ATM-Blatt V56-2, Archiv für Technisches Messen, Lieferung 198, 151-152.

van Dongen, J.E.F. (**2001**). Noise annoyance from neighbours and the impact of sound insulation and other factors. Proceedings of the 30th International Congress and Exposition on Noise Control Engineering (InterNoise), The Hague, The Netherlands.

Venegas, R., Nabuco, M., Massarani, P. (**2006**). Sound Insulation Evaluation Using Transfer Function Measurements. *Journal of Building Acoustics*, **13** (1), 23-31.

Vian, J.-P., Danner, W.F., and Bauer, J.W. (**1983**). Assessment of significant acoustical parameters for rating sound insulation of party walls. *Journal of the Acoustical Society of America,* **73**, 1236-1243.

von Bismarck, G. (**1974**). „Sharpness as an attribute of the timbre of steady sounds“, *Acustica* **30**, 159-172.

Vorländer, M., Kob, M. (**1997**). Practical aspects of MLS Measurements in Building Acoustics. *Applied Acoustics*, **52**, 239-258.

Vorländer, M.; Thaden, R. (**2000**). Auralisation of Airborne Sound Insulation in Buildings. *Acta Acustica united with Acustica*, **86** (1), 70-76.

Vorländer, M. (**2006**). Building acoustics: From prediction models to auralization. Proceedings of Acoustics 2006, Christchurch, New Zealand, 15-22.

Wang, Y.S., Shen, G.Q., Gua, H., Tang, X.L., Hamade, T. (**2013**). Roughness modelling based on human auditory perception for sound quality evaluation of vehicle interior noise. *Journal of Sound and Vibration,* **332**, 3893-3904.

Waterhouse, R.V. (**1955**). Interference Patterns in Reverberant Sound Fields. *Journal of the Acoustical Society of America,* **27** (2), 247-258.

Watters, B. G. (**1959**). Transmission Loss of Some Masonry Walls. *Journal of the Acoustical Society of America,* **31** (7), 898-911.

WHO (**2009**). Night Noise Guidelines for Europe. The World Health Organization, Geneva, Switzerland. http://www.euro.who.int/document/e92845.pdf.

Waugh, D. (**2002**). Environmental Quality Objectives For Noise In Relatively Quiet Areas And Its Potential Impact On The Mining And Quarrying Industry. SWS Environmental Services, Shinagh House, Bandon, Co. Cork, Ireland.

Warnock, A.C.C., Vorländer, M. (**1993**). Inter-Laboratory Comparison of Low Frequency Sound Transmission. Part II: Narrow-Band Measurements and Computer Simulations. Proceedings of the 22th International Congress and Exposition on Noise Control Engineering (InterNoise), Leuven, Belgium, 929-932.

Warnock, A.C.C. & Birta, J.A. (**2000**). "Detailed Report for Consortium on Fire Resistance and Sound Insulation of Floors: Sound Transmission and Impact Insulation Data in 1/3 Octave Bands", National Research Council of Canada, Internal Report No. 811.

Weston, E. T.; Green, R. G. (**1969**). Methods of Achieving Airborne Sound Insulation. Proceedings of the 1969 Conference of the Australian Acoustical Society (A.A.S.), Noise reduction of Floors, Walls, and Ceilings, Hotel Florida, Terrigal, 11th, 12th October 1969, Paper B.

Wittstock, V. (**2007**). On the Uncertainty of Single-Number Quantities for Rating Airborne Sound Insulation. *Acta Acustica united with Acustica*, **93** (3), 375-386.

Wittstock, V. (**2005**). Uncertainties in building acoustics. Proceedings of the 4th European Congress on Acoustics (Forum Acusticum), Budapest, Hungary.

Yaniv, S. L., Flynn , D. R., (**1978**) "Noise Criteria for Buildings: A Critical Review", Special Publication SP 499, National Bureau of Standards, U.S. Department of Commerce, Washington, D.C., USA.

Yifan, H., Guoqing, D., Yiting, Z., Youpeng, H., Bangjun, Z. (**2008**). Pair-wise comparison experiment on subjective annoyance rating of noise samples with different frequency spectrums but same A-weighted level. *Journal of Applied Acoustics,* **69**, 1205-1211.

Zwicker, E. (**1958**). "Über psychologische und methodische Grundlagen der Lautheit", (About psychological and methodological basics of loudness), (in German). *Acustica*, **8**, Supplement 1, 237-258 (22).

Zwicker, E. (**1960**). "Ein Verfahren zur Berechnung der Lautstärke", (A method for calculating loudness level), (in German). *Acustica*, **10**, Supplement 1, 304-308(5).

Zwicker, E., Scharf, B. (**1965**). "A model of loudness summation". *Psychological Review*, **72** (1), 3-26.

Zwicker, E. (**1977**). Procedure for calculating loudness of temporally variable sounds. *Journal of the Acoustical Society of America,* **62**, 675.

Zwicker, E. (**1985**). What is a meaningful value for quantifying noise reduction? Proceedings of the 14th International Congress on Noise Control Engineering (InterNoise), Munich, Germany, 47-56.

Zwicker, E., Fastl, H. (**1999**). *Psychoacoustics. Facts and Models*. 2nd Updated Edition, Springer-Verlag Berlin Heidelberg New York.

APPENDICES

Appendix I: Reference values for airborne sound according to ISO 717-1

Frequency, Hz	Reference values, dB
100	33
125	36
160	39
200	42
250	45
315	48
400	51
500	52
630	53
800	54
1,000	55
1,250	56
1,600	56
2,000	56
2,500	56
3,150	56

Appendix II: Sound spectra to calculate the adaptation terms according to ISO 717-1

Frequency	Sound levels, L_{ij}, dB	
Hz	Spectrum No. 1 to calculate C	Spectrum No. 2 to calculate C_{tr}
100	– 29	– 20
125	– 26	– 20
160	– 23	– 18
200	– 21	– 16
250	– 19	– 15
315	– 17	– 14
400	– 15	– 13
500	– 13	– 12
630	– 12	– 11
800	– 11	– 9
1,000	– 10	– 8
1,250	– 9	– 9
1,600	– 9	– 10
2,000	– 9	– 11
2,500	– 9	– 13
3,150	– 9	– 15

NOTE All levels are A-weighted and the overall spectrum level is normalized to 0 dB.

Appendix III: Calculation procedure for the simplified model according to EN 12354-1

The weighted apparent sound reduction index is determined from Eq. (AIII-1):

$$R'_w = -10lg\left[10^{-\frac{R_{Dd,w}}{10}} + \sum_{F=f=1}^{n} 10^{-R_{Ff,\frac{w}{10}}} + \sum_{f=1}^{n} 10^{-R_{Df,\frac{w}{10}}} + \sum_{F=1}^{n} 10^{-R_{Fd,\frac{w}{10}}}\right] \quad (AIII-1)$$

where:

$R_{Dd,w}$: is the weighted sound reduction index for direct transmission, (dB)

$R_{Ff,w}$: is the weighted flanking sound reduction index for the transmission path Ff, (dB)

$R_{Df,w}$: is the weighted flanking sound reduction index for the transmission path Df, ((dB)

$R_{Fd,w}$: is the weighted flanking sound reduction index for the transmission path Fd, ((dB)

$$R_{Dd,w} = R_{s,w} + \Delta R_{Dd,w} \quad (AIII-2)$$

where:

$R_{s,w}$ is the weighted sound reduction index of the separating element, dB

$\Delta R_{Dd,w}$ is the total weighted sound reduction index improvement by additional lining on the source and/or receiving side of the separating element, dB

The weighted flanking sound reduction indices are determined from the input values according to the following:

$$R_{Ff,w} = \frac{R_{F,w} + R_{f,w}}{2} + \Delta R_{Ff,w} + K_{Ff} + 10log\frac{S_s}{l_0 l_f} \ dB \quad (AIII-3)$$

$$R_{Fd,w} = \frac{R_{F,w} + R_{s,w}}{2} + \Delta R_{Fd,w} + K_{Fd} + 10log\frac{S_s}{l_0 l_f} \ dB \quad (AIII-4)$$

$$R_{Df,w} = \frac{R_{s,w} + R_{f,w}}{2} + \Delta R_{Df,w} + K_{Df} + 10log\frac{S_s}{l_0 l_f} \ dB \quad (AIII-5)$$

where:

$R_{F,w}$: is the weighted sound reduction index of the flanking element F in the source room, (dB)

$R_{f,w}$: is the weighted sound reduction index of the flanking element f in the receiver room, (dB)

$\Delta R_{Ff,w}$: is the total weighted sound reduction index improvement by additional lining on the source and/or receiving side of the flanking element, (dB)

$\Delta R_{Fd,w}$: is the total weighted sound reduction index improvement by additional lining on the flanking element at the source side and/or separating element at the receiving side, (dB)

$\Delta R_{Df,w}$: is the total weighted sound reduction index improvement by additional lining on the separating element at the source side and/or flanking element at the receiving side, (dB)

K_{ij}: is the vibration reduction index of the transmission path ij = *Ff*, *Fd* or *Df*, respectively, (dB)

S_s: is the area of the separating element, (m^2)

l_f: is the common coupling length of the junction between separating element and the flanking elements *F* and *f*, (dB)

l_0: is the reference coupling length, l_0 = 1m.

The different contributions to the total sound transmission to a room are shown in the Figure below for clarity.

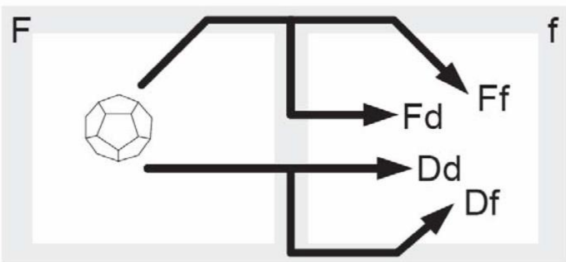


Figure AIII-1: Description of the paths of the sound transmission:

d – direct path, *f* – flanking path

Appendix IV, a): Transformation of SPL into Loudness Level (L_N) according to ISO 226

In order to calculate the sound insulation value the sound pressure levels have to be transformed into loudness level.

$$B_f = \left[0.4 * 10^{\left(\frac{L_p+L_U}{10}-9\right)}\right]^{a_f} - \left[0.4 * 10^{\left(\frac{T_f+L_U}{10}-9\right)}\right]^{a_f} + 0.005135 \qquad \text{(AIV, a-1)}$$

$$L_N = \left(40 * lg\ B_f\right) phon + 94\ phon \qquad \text{(AIV, a-2)}$$

were

L_N Loudness level in phon for a pure tone of frequency *f*

L_p Sound pressure level in dB of a pure tone of frequency *f* which has a loudness level L_N

a_f Exponent for loudness perception

L_U Magnitude of the linear transfer function normalized at 1 kHz in dB

T_f Threshold of hearing in dB

The parameter: a_f, L_u, and T_f , respectively for the calculation of the curves are depicted in Appendix IV, b).

Appendix IV, b): Calculation of the curves of equal-loudness according to ISO 226

Parameter for the calculation of the curves of equal-loudness (ISO 226)

Frequency f **Hz**	a_f	L_u **dB**	T_f **dB**
20	0.556	-30.4	76.6
25	0.525	-26.5	67.3
31.5	0.495	-22.7	58.4
40	0.465	-19.2	50.2
50	0.439	-16.1	43.2
63	0.414	-13.3	36.7
80	0.389	-10.6	30.7
100	0.368	-8.4	25.7
125	0.349	-6.4	21.3
160	0.329	-4.5	17.0
200	0.313	-3.1	13.6
250	0.299	-1.9	10.7
315	0.286	-0.9	8.0
400	0.275	-0.2	5.7
500	0.266	0.3	3.9
630	0.258	0.5	2.5
800	0.253	0.5	1.9
1,000	0.250	0.0	2.2
1,250	0.247	-2.2	3.2
1,600	0.246	-3.0	1.8
2,000	0.246	-0.2	-1.2
2,500	0.246	2.2	-4.3
3,150	0.246	3.1	-6.3
4,000	0.246	2.0	-6.0
5,000	0.246	-1.0	-2.5
6,300	0.248	-5.9	5.4
8,000	0.256	-10.1	13.4
10,000	0.270	-10.2	15.0
12,500	0.295	-3.7	15.6

Appendix V, a): Definitions of psychoacoustic parameters, Sharpness and Tonality.

Sharpness (S)

Sharpness is a measure of the high frequency content of a sound. Sharpness is linked to the spectral characteristics of the sound and is calculated from specific loudness *N′*. This metric is measured in acum. The sensation of sharpness results from high-frequency components in acoustic signals and is defined as a linear perception dimension. The sharpness of narrowband noise of 1k Hz, bandwidth less than 150 Hz (critical bandwidth) and level of 60 dB is defined as 1 acum. The calculation of sharpness vs. time is standardized in DIN 45692 (2009). Other models exist e.g. the model of von Bismark (1974) or Aures (1985).

The calculation in this study was done using the model in DIN 45692 implemented in the software ArtemiS V 11 of Head acoustics.

Calculation methods according to *DIN*, *Aures* and *von Bismarck*

DIN

$$S = 0.11 \cdot \frac{\int_0^{24\,Bark} n'(z) \cdot z \cdot g(z) dz}{N}$$

$$g(z) = \begin{cases} 1 & (z \leq 15.8 Bark) \\ 0.85 + 0.15 \cdot e^{0.42(z-15.8)} & (z > 15.8 Bark) \end{cases} \qquad \text{(AV, a-1)}$$

Aures

$$S = K_1 \cdot \frac{\int_0^{24\,Bark} n'(z) \cdot e^{0.171z} dz}{\ln(\frac{N}{20} + 1)}$$

von Bismarck

$$S = K_2 \cdot \frac{\int_0^{24\,Bark} n'(z) \cdot z \cdot g(z) dz}{N}$$

$$g(z) = \begin{cases} 1 & (z < 14 Bark) \\ 1 + 0.003 \cdot (z - 14 Bark)^3 & (z \geq 14 bark) \end{cases}$$

$n'(z)$ = Specific loudness

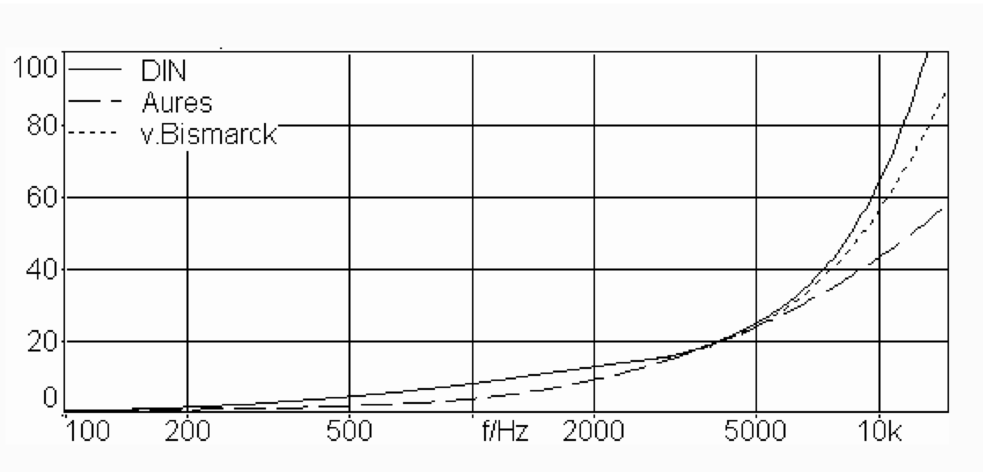
z= Tonality (Bark)

N= Total loudness

K_n = Scaling factors

g’(z) is a critical-band-rate dependent factor. This factor does only for critical-band rates larger than z = 16 Bark (3,150 Hz) increase from unity to a value of four at the end of the critical-band rate near z = 24 Bark (15,500 Hz). This takes into account that sharpness of narrow-band noises increases unexpectedly strongly at high centre frequencies (Zwicker and Fastl, 1999).

Besides the different weighting curves for the specific loudness (see picture below) there is a difference in the denominator. Whereas the DIN and v. Bismarck formulas give the same results for different total loudness values as long as the specific loudness distribution is the same, Aures' formula will give higher sharpness values with increasing total loudness.
The different results are presented graphically in the used software in the help file from which the figure below is taken as a copy:



Copy taken from: ArtemiS V11.00.200, HEAD acoustics GmbH, Germany

Tonality (Ton)

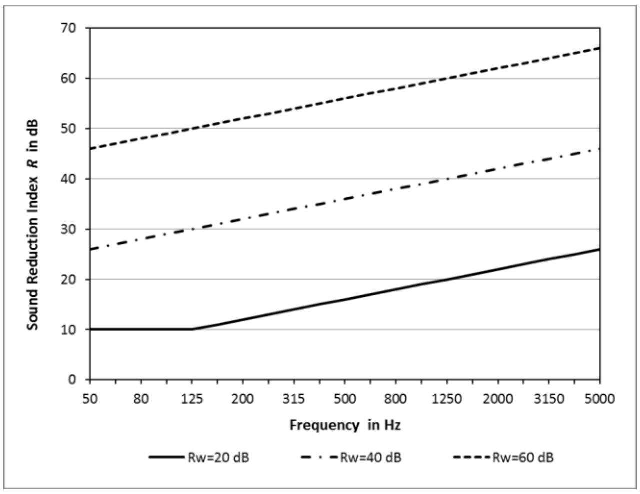
Tonality is the degree to which a noise contains audible pure tones. It measures the number of pure tones in the noise spectrum. This metric is measured in tu.

The calculation of tonality is based on publications by Terhardt, et al., (1982)

As stated in the handbook of the software ArtemiS: "*Tonality is a measure of the proportion of tonal components in the spectrum of a signal and allows a distinction between tones and noises. Tones consist mainly of tonal components which show in the spectrum as pronounced peaks. Noise and broadband noises have no or little tonality. A constant in tonality calculation K achieves that a value of 1 tu results from a sine tone of 1k Hz and 60 dB.*" (HEAD Acoustics GmbH, 2014).

Sottek (2014, 2015) has mentioned that the method to quantify the tonality of identified discrete tones do not respond well or even at all to tonalities caused by narrow bands of noise or non-pure tones, and thus are particularly useless with many frequently-encountered tonalities.

Appendix V, b): Calculated psychoacoustic parameters for different sound signals using filter coefficients for R_w = 20 dB, 40 dB, and 60 dB.



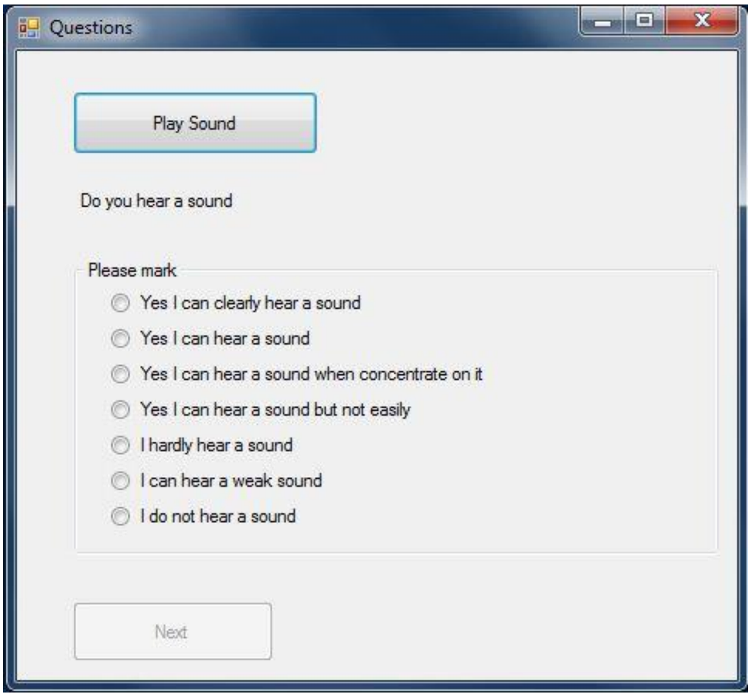
Frequency depending filter coefficients for R_w = 20 dB, 40 dB, and 60 dB.

Calculated parameters using above filter coefficients. R_w = 0 dB indicates L_1 = 85 dB.

PN	*R' (asper)*	*S (acum)*	*Ton (tu)*	*Fls' (vacil)*	*L_N (phon)*	*N (sone)*	*SPL (dB)*
R = 0 dB	3.9500	2.140	0.0170	0.02250	99.1	60.000	85.0
R = 20 dB	2.0400	1.540	0.0180	0.01480	81.3	17.500	71.2
R = 40 dB	0.7980	1.420	0.0202	0.00849	60.7	4.190	53.1
R = 60 dB	0.0226	0.915	0.0096	0.00477	26.7	0.314	33.1
WN							
R = 0 dB	3.6200	2.790	0.0197	0.01660	98.5	57.600	85.0
R = 20 dB	1.8300	2.150	0.0231	0.01200	79.0	15.000	61.2
R = 40 dB	0.5780	2.200	0.0256	0.00689	57.8	3.440	41.7
R = 60 dB	**0.0000**	2.170	**0.0000**	0.00387	22.2	0.185	21.7
B							
R = 0 dB	3.4700	1.430	0.1810	0.18200	97.2	53.700	85.0
R = 20 dB	1.7500	1.090	0.2180	0.10900	79.9	16.300	68.3
R = 40 dB	0.6740	0.936	0.2620	0.06110	59.3	3.970	49.0
R = 60 dB	0.0121	0.781	0.2670	0.03440	29.9	0.484	29.0
E							
R = 0 dB	3.6300	1.600	0.1820	0.22300	94.8	45.900	85.0
R = 20 dB	1.7400	1.150	0.2240	0.13500	77.5	13.900	72.5
R = 40 dB	0.4720	0.993	0.2630	0.07740	56.0	3.2200	54.5
R = 60 dB	0.0315	0.601	0.2280	0.04350	23.7	0.2670	34.5
PS							
R = 0 dB	2.9000	1.580	0.2340	0.12900	94.8	45.200	85.0
R = 20 dB	1.4700	1.090	0.2780	0.11000	78.2	14.300	72.7
R = 40 dB	0.3520	0.837	0.3230	0.06590	57.0	3.330	54.4
R = 60 dB	0.0338	0.427	0.4390	0.03710	27.2	0.356	34.4

Appendix VI, a): Questionnaire, response scale, and results for the 1st listening test.

For reference see section 5.2.1

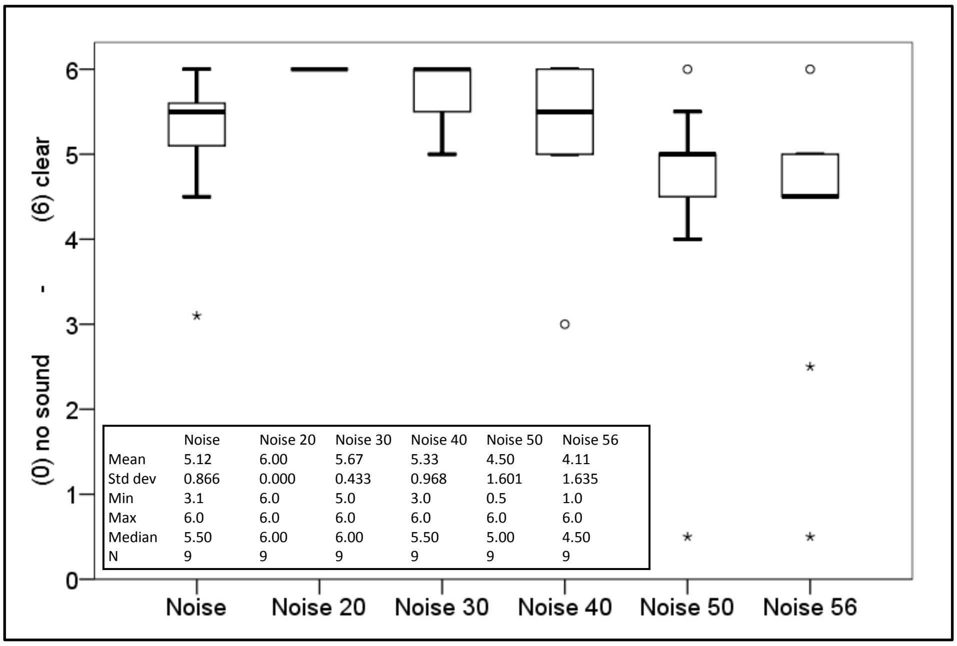


1 'clear' 2 'hear' 3 'concentrate' 4 'not easy' 5 'hardly' 6 'weak' 7 'no sound

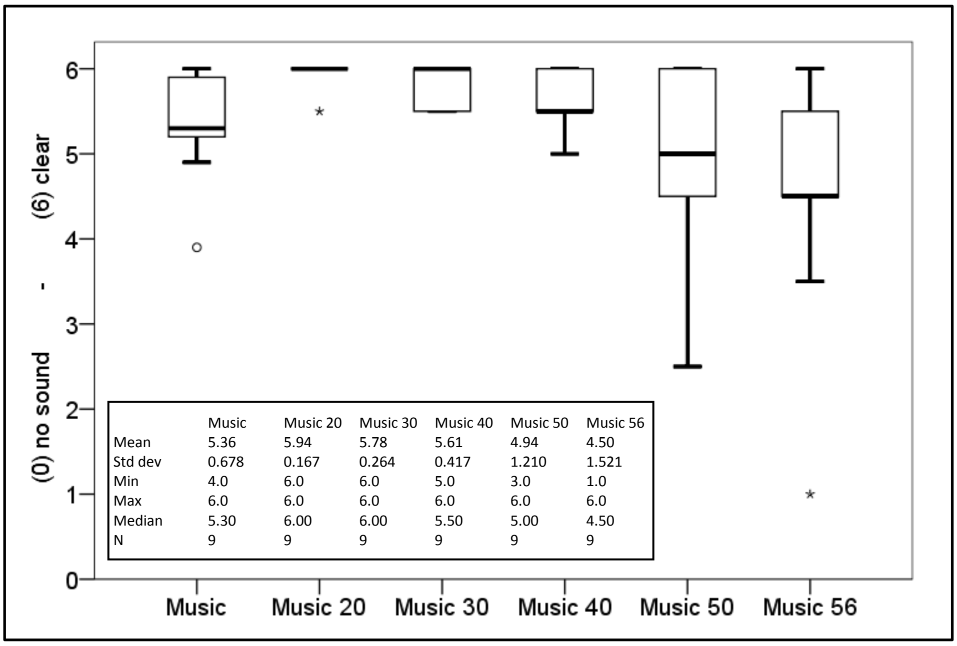
	Sound sample																			
	WN					**PN**					**E**					**B**				
	Sound insulation / sound reduction index R (dB)																			
Participant	20	30	40	50	56	20	30	40	50	56	20	30	40	50	56	20	30	40	50	56
1	1	2	2	2	3	1	2	2	2	2	1	1	1	2	2	1	2	2	3	3
2	1	2	2	3	5	1	2	2	3	4	1	2	2	3	3	1	1	1	2	2
3	1	1	1	2	3	1	1	1	2	2	1	1	2	2	3	1	1	2	2	2
4	1	1	1	2	2	1	2	2	3	3	1	1	1	1	1	1	1	1	1	1
5	1	1	2	2	2	1	1	1	2	2	1	1	1	1	1	1	1	1	1	2
6	1	2	6	7	7	1	1	2	6	6	1	1	2	5	6	2	2	2	4	6
7	1	1	1	2	3	1	1	1	1	2	1	1	1	1	1	1	1	1	1	2
8	1	1	1	2	2	1	1	1	2	2	1	2	1	3	3	1	1	2	3	4
9	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2

Appendix VI, b)

Descriptive statistics



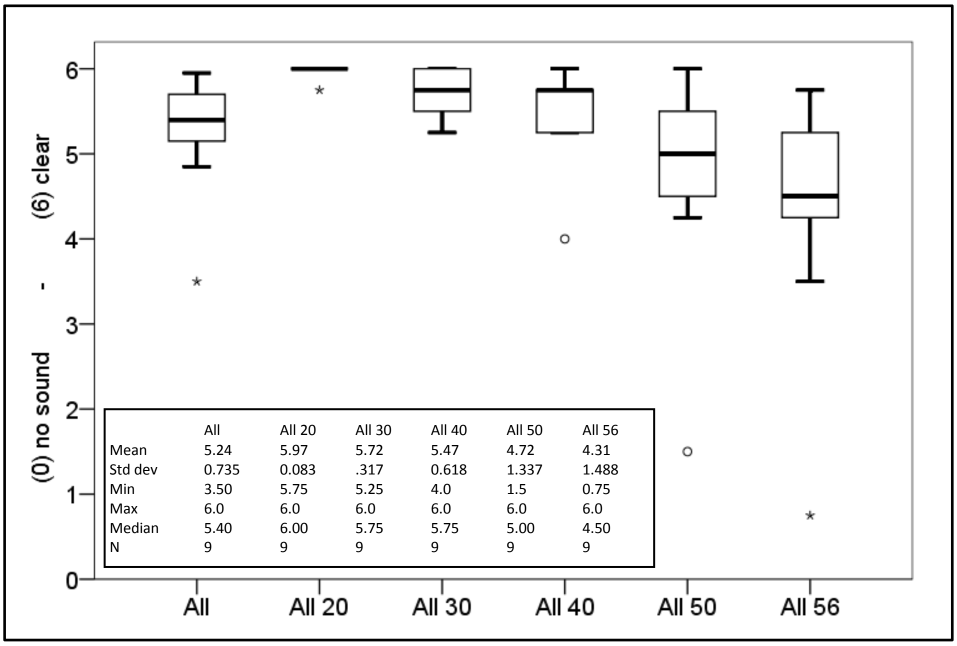
	Noise	Noise 20	Noise 30	Noise 40	Noise 50	Noise 56
Mean	5.12	6.00	5.67	5.33	4.50	4.11
Std dev	0.866	0.000	0.433	0.968	1.601	1.635
Min	3.1	6.0	5.0	3.0	0.5	1.0
Max	6.0	6.0	6.0	6.0	6.0	6.0
Median	5.50	6.00	6.00	5.50	5.00	4.50
N	9	9	9	9	9	9



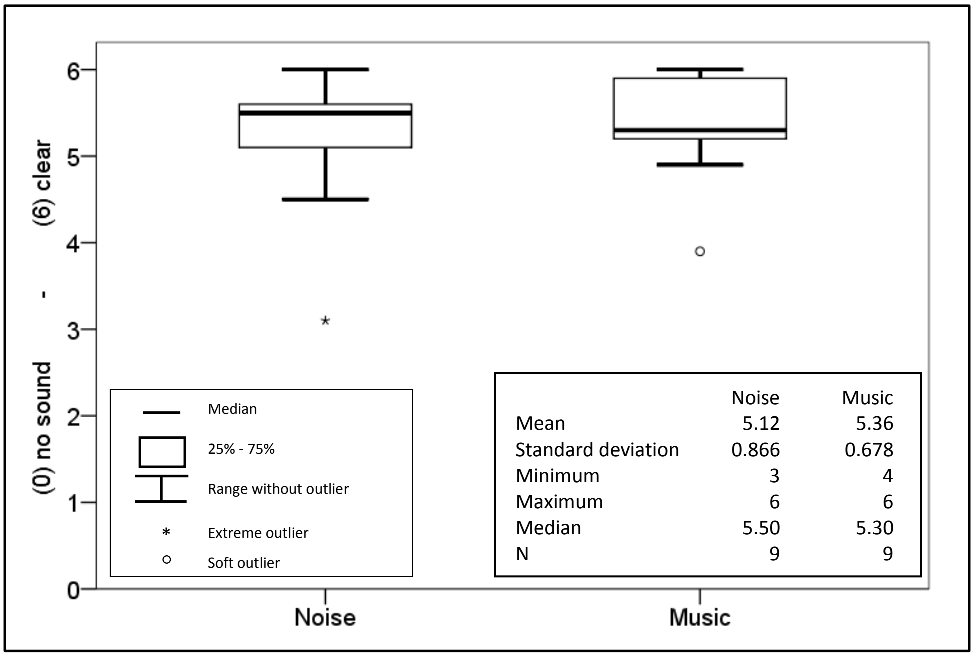
	Music	Music 20	Music 30	Music 40	Music 50	Music 56
Mean	5.36	5.94	5.78	5.61	4.94	4.50
Std dev	0.678	0.167	0.264	0.417	1.210	1.521
Min	4.0	6.0	6.0	5.0	3.0	1.0
Max	6.0	6.0	6.0	6.0	6.0	6.0
Median	5.30	6.00	6.00	5.50	5.00	4.50
N	9	9	9	9	9	9

Appendix VI, c)

Descriptive statistics



	All	All 20	All 30	All 40	All 50	All 56
Mean	5.24	5.97	5.72	5.47	4.72	4.31
Std dev	0.735	0.083	.317	0.618	1.337	1.488
Min	3.50	5.75	5.25	4.0	1.5	0.75
Max	6.0	6.0	6.0	6.0	6.0	6.0
Median	5.40	6.00	5.75	5.75	5.00	4.50
N	9	9	9	9	9	9



	Noise	Music
Mean	5.12	5.36
Standard deviation	0.866	0.678
Minimum	3	4
Maximum	6	6
Median	5.50	5.30
N	9	9

Appendix VII, a): Questionnaire, response scale, and results for the 2nd listening test.

For reference see section 5.2.2

Test	Much Louder					equally loud					much quieter
	-5	-4	-3	-2	-1	0	+1	+2	+3	+4	+5
1	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑
…	…	…	…	…	…	…	…	…	…	…	…
30	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑

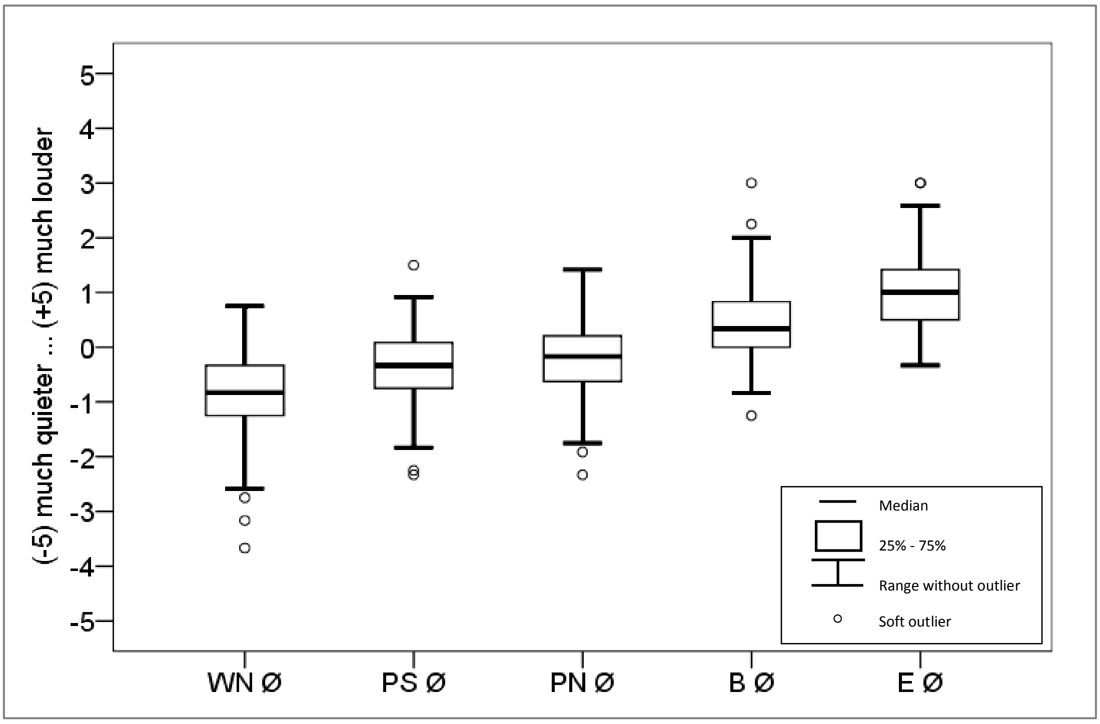
Was the second sound sample when compared to the first …?

Test					
5 Signals	Noise1				
	Noise2				
	Music1				
	Music2				
	Party Sound				
3 SPL (dB)	20				
	40				
	60				
	Sound	*SPL*		*Sound*	*SPL*
1	Noise1	20	vs.	Noise2	20
2	Noise1	20	vs.	Music1	20
3	Noise1	20	vs.	Music2	20
4	Noise1	20	vs.	Party Sound	20
5	Noise2	20	vs.	Music1	20
6	Noise2	20	vs.	Music2	20
7	Noise2	20	vs.	Party Sound	20
8	Music1	20	vs.	Music2	20
9	Music1	20	vs.	Party Sound	20
10	Music2	20	vs.	Party Sound	20
11	Noise1	40	vs.	Noise2	40
12	Noise1	40	vs.	Music1	40
13	Noise1	40	vs.	Music2	40
14	Noise1	40	vs.	Party Sound	40
15	Noise2	40	vs.	Music1	40
16	Noise2	40	vs.	Music2	40
17	Noise2	40	vs.	Party Sound	40
18	Music1	40	vs.	Music2	40
19	Music1	40	vs.	Party Sound	40
20	Music2	40	vs.	Party Sound	40
21	Noise1	60	vs.	Noise2	60
22	Noise1	60	vs.	Music1	60
23	Noise1	60	vs.	Music2	60
24	Noise1	60	vs.	Party Sound	60
25	Noise1	60	vs.	Music1	60
26	Noise1	60	vs.	Music2	60
27	Noise1	60	vs.	Party Sound	60
28	Music1	60	vs.	Music2	60
29	Music1	60	vs.	Party Sound	60
30	Music2	60	vs.	Party Sound	60

Appendix VII, b): Response sheet

Partisip.	Test 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	2	1	-2	0	2	0	0	-2	-1	0	-1	0	-1	-1	0	0	-1	0	-2	0	0	2	-2	0	2	-2	0	-1	-1	0
2	-2	2	2	1	1	0	-1	1	-1	0	0	-2	1	-2	0	0	0	1	0	-1	-2	3	3	3	3	3	2	0	-1	1
3	0	0	0	-2	1	-1	0	-1	-1	0	0	1	0	-3	-3	-1	-1	-2	-3	-3	2	2	2	1	3	2	0	-1	-1	-1
4	0	0	0	-1	-1	-1	-1	-1	-1	-1	-3	-5	-5	-5	-5	-5	-5	-5	-5	-5	5	5	5	5	5	5	5	5	5	3
5	-2	0	1	1	1	1	0	0	-1	0	-1	1	1	1	1	1	0	0	-1	0	-1	1	1	1	1	1	1	0	0	-1
6	-1	-2	-1	-1	1	1	-1	0	0	0	0	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	-1	2	0	-1	1	0	-1	0	-1	0	-1	0	-1	-2	-2	0	0	0	-1	0	-1	4	4	5	4	2	1	0	-1	0
8	-2	3	1	0	2	0	-1	1	-1	-1	-3	0	-1	-2	0	1	-1	0	-1	-1	0	3	2	1	2	1	0	-1	0	1
9	0	3	-1	1	5	1	0	-1	1	0	-2	2	0	-1	2	0	-1	0	-2	0	-2	5	-1	0	5	0	0	-1	-2	-2
10	-2	3	1	-1	5	2	-2	0	-1	-1	-3	1	1	-2	-2	1	-1	0	-3	-3	-3	4	4	3	5	3	-2	-1	-3	0
11	-2	3	-5	-1	5	3	-3	0	1	-2	-3	2	3	-4	1	-2	-4	2	-3	-4	3	4	5	4	4	4	-3	3	-4	-4
12	-2	3	4	1	5	3	1	-2	-2	-2	0	2	-2	0	-2	0	0	0	-3	0	-2	1	1	0	3	2	0	-1	-2	-2
13	-3	4	4	3	4	4	2	4	-2	-3	-4	-1	0	0	2	2	1	2	-1	-1	-2	2	2	2	3	2	2	-1	-1	0
14	2	0	0	-2	0	2	-2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	1	2	2	0	0	0	0
15	-2	3	2	0	3	2	-1	2	-2	-2	0	1	1	-4	2	2	-3	-1	-4	-4	-3	1	-2	-1	3	2	-2	-2	-3	-2
16	-2	2	0	-1	2	1	0	-2	0	-2	-1	0	-2	-2	-2	-3	-3	-2	-3	-1	0	3	2	1	3	2	2	0	-2	0
17	-2	2	0	-1	2	1	0	-2	0	-2	-1	0	-2	-2	-2	-3	-3	-2	-3	-1	-1	3	2	1	3	2	2	0	-2	0
18	-1	1	0	-1	1	0	-1	0	-1	1	-1	-1	1	0	-1	1	-1	2	-1	0	2	4	1	2	4	4	3	-2	-2	1
19	-1	2	1	1	2	2	1	0	1	0	-2	-2	0	-1	0	-1	0	0	0	0	-2	3	2	2	3	1	2	1	1	2
20	-2	4	3	2	4	1	2	-2	-3	0	-1	3	2	0	4	1	0	0	-2	1	0	3	4	3	5	3	5	-1	0	3
21	-2	4	2	3	4	2	3	4	2	3	0	4	2	0	0	0	0	0	0	0	-2	4	1	3	3	2	2	0	2	0
22	0	1	0	1	1	0	0	-1	-1	0	0	-1	0	-2	0	0	-2	0	-1	-1	0	1	1	0	2	1	0	-1	-1	0
23	-3	5	-1	-3	4	-2	2	-1	-2	-2	-2	2	-2	0	0	-2	-3	0	-2	-2	-2	0	0	3	4	0	0	-1	0	0
24	-1	2	0	-1	4	-1	0	0	-2	0	-2	0	1	-3	0	-1	0	1	-1	0	-1	4	-1	2	3	1	0	0	1	0
25	-2	2	-1	-1	3	0	-3	0	-2	-1	-4	-1	0	-4	-1	1	-2	1	0	-1	0	3	4	2	4	0	1	0	-2	-1
26	-1	0	0	0	1	0	1	0	0	0	-2	0	0	-1	1	2	1	0	0	0	-1	2	0	0	2	0	1	0	0	0
27	-1	0	0	-1	0	0	-1	-1	-1	-1	-2	-1	0	-1	0	0	-2	0	0	0	0	1	2	1	2	0	1	0	0	0
28	0	-1	-3	0	3	-2	-1	0	-2	0	-1	0	0	-1	1	0	-1	1	-1	0	0	2	2	0	1	0	1	-1	0	0
29	-2	5	1	0	1	0	0	-1	0	-1	1	0	-1	-1	0	0	0	0	0	-1	-1	4	1	1	4	0	1	0	0	0
30	-2	1	1	-1	1	0	-2	-2	0	1	-2	-1	1	-2	-1	-1	0	0	0	0	0	4	1	1	3	1	1	0	-1	0
31	-2	2	0	-2	2	0	-3	-2	-1	0	-1	-4	-4	-4	-3	0	-2	0	-2	-2	-2	2	0	-1	3	2	0	1	0	1
32	-2	2	2	3	-2	-3	0	0	-2	0	3	3	2	-1	-2	0	0	-1	-1	0	5	5	2	4	3	4	3	5	2	3
33	-2	2	2	2	0	2	2	2	1	1	-1	0	0	-2	1	0	0	-1	0	0	-3	2	0	-1	3	-1	2	-2	-1	0
34	-2	0	0	-1	2	-1	0	-1	-1	0	-1	0	-1	-2	0	-1	-1	0	-1	0	-1	3	0	1	2	-1	1	-1	0	1
35	-3	4	-2	2	5	3	2	-3	-2	-4	-5	-1	0	-2	2	3	1	0	-2	-4	-5	5	5	5	5	5	5	5	-1	0
36	-1	4	0	-1	1	-1	0	2	0	1	0	-2	-1	-1	0	-1	-2	0	0	-1	-2	3	2	2	1	1	1	0	1	0
37	-1	2	3	2	3	2	-2	0	-1	0	-1	-3	-2	-4	-2	-2	-3	0	-2	-4	-1	4	1	3	4	3	2	0	-1	0
38	-1	2	0	1	1	1	1	0	0	0	-1	-1	0	-1	-1	1	-1	1	-1	0	1	2	1	0	2	1	2	1	-1	1
39	-2	2	-1	0	1	0	-1	-1	-2	-1	-2	-1	0	-1	1	-1	-1	-1	-1	0	-2	3	2	2	3	2	2	1	-1	0
40	-2	3	1	1	2	0	1	-2	-2	1	0	1	0	-1	1	0	1	-1	-1	0	3	5	0	1	1	0	1	-1	-1	0
41	-3	2	0	-1	1	0	-1	0	-2	0	-4	0	-1	-2	0	1	-2	1	-1	0	-3	0	1	0	3	1	2	-1	0	0
42	0	2	1	-1	3	0	-1	0	-3	1	1	-1	2	-2	3	0	-3	0	-4	1	-1	4	3	4	5	3	0	0	-1	0
43	-2	2	1	0	3	-1	0	-2	-2	0	-3	2	0	1	2	1	1	-2	-1	0	-1	2	1	2	3	0	1	-2	0	1
44	-2	2	1	0	1	-1	1	-2	-1	-1	-3	-1	-2	-3	0	-1	-3	1	-2	-1	-3	2	2	3	3	2	3	-1	0	0
45	-1	1	1	-1	0	-1	-2	-1	2	1	2	-3	-3	-4	-2	0	-1	0	-2	0	-1	3	1	2	3	1	2	0	-1	1
46	-1	1	-1	-1	2	0	0	-1	-1	0	-1	0	0	-1	0	1	0	0	0	0	-1	3	0	1	1	1	1	-1	0	1
47	-3	2	0	-1	2	0	0	1	-1	-1	-3	-2	-1	0	0	1	0	1	-2	-1	-1	0	-1	-1	1	0	0	0	-2	0
48	-3	2	0	2	4	1	0	2	1	0	-2	-1	0	-2	1	0	-1	1	1	0	-4	5	2	2	3	0	1	0	-1	0
49	-2	3	-1	-2	3	1	-1	-1	-3	-2	-3	-1	-2	-2	0	0	0	-1	-2	-1	-2	4	4	0	5	3	0	0	-1	1
50	-2	2	1	-3	3	1	-2	-1	-1	-2	-3	-4	-2	-4	1	0	-1	0	-1	-2	1	2	1	0	4	1	0	-1	-2	0
51	1	1	1	2	2	2	2	1	0	-1	1	1	2	1	2	2	0	-1	0	-1	-1	3	3	-2	3	1	2	0	-1	0
52	2	2	2	0	5	1	1	-2	-5	-5	-5	2	1	0	3	0	-2	-3	-2	0	-2	0	2	4	5	5	3	-3	-4	3
53	-2	1	-1	-1	1	0	-2	-3	-3	-1	1	-1	-4	-5	1	0	-3	1	-2	0	0	0	1	-1	2	1	0	-1	-1	0
54	0	2	-1	0	1	-2	-2	0	-2	0	0	-3	-1	-1	-3	0	1	0	-1	0	0	-1	-1	-1	-2	0	1	-1	0	0
55	-1	-1	-1	-1	-1	-1	-1	-2	0	0	0	0	-1	0	-1	-1	0	0	0	0	-3	-3	-3	-3	-3	-3	0	-3	-3	0
56	-1	2	3	-2	0	0	0	-1	-2	0	-2	-2	0	-3	-1	-1	-1	0	0	-1	0	2	0	1	3	0	1	-1	-1	1
57	-2	3	0	1	3	0	-1	-2	-3	-1	-2	2	0	-1	2	0	-1	0	-2	-2	-2	2	0	-1	2	0	-1	-2	-2	-2
58	-1	2	2	2	3	0	0	-1	0	0	-1	0	0	0	-1	-1	0	0	0	0	-1	2	1	2	3	2	1	0	0	1
59	-3	0	0	-1	1	0	0	-1	0	-1	0	-1	-2	-2	0	-1	0	0	0	0	0	1	1	0	2	0	0	-1	-3	0
60	-1	1	0	-1	2	0	-3	2	-2	-2	0	-1	1	-2	0	1	-2	1	-2	-3	2	3	2	-1	1	0	-1	-1	-2	-1
61	0	-1	2	1	2	0	0	1	-1	-1	-2	-1	-1	-2	-1	0	-2	-1	-2	-2	4	5	5	4	5	5	4	5	4	4
62	-3	4	1	-3	2	0	-1	-3	-2	1	-4	-4	1	-3	-1	2	-4	1	-2	-3	0	4	4	5	5	4	1	-1	0	-1
63	3	5	-1	1	5	1	2	-2	-3	-1	-1	2	-1	-3	3	-1	1	-1	-2	-1	1	5	1	2	5	2	1	-2	-1	-1
64	1	2	1	2	4	-1	1	3	-2	1	0	2	0	-1	2	2	1	2	0	0	1	5	2	2	5	1	0	1	1	0
65	-1	1	0	-1	-1	-2	-2	-1	-2	0	-1	-2	0	-3	-1	0	-2	1	0	-2	0	1	2	2	3	0	1	2	-1	0
66	-3	-1	0	2	3	-1	2	0	0	-1	-3	2	0	0	2	-1	1	0	-2	0	-3	2	1	0	3	2	2	0	-1	0
67	-3	3	1	0	1	0	1	0	-2	-1	-3	0	0	-2	0	1	0	0	-2	-1	-1	3	2	1	2	2	1	0	0	0
68	-2	3	1	0	1	-1	-1	-2	-2	1	-2	0	-2	-3	1	1	-1	1	-2	-2	0	2	3	1	1	2	1	0	-1	0
69	-3	4	4	0	1	4	-1	2	-2	2	1	0	2	-2	-2	0	-1	3	0	1	4	0	3	1	4	2	1	-2	0	1
70	1	1	3	1	2	3	2	3	-1	0	-1	-1	1	-1	1	2	0	0	0	0	1	3	5	3	5	4	3	0	0	0
71	-2	3	2	0	2	1	0	-1	-2	-3	-2	0	1	0	0	0	-2	1	-1	-3	-2	5	5	2	3	4	2	0	-2	-1
72	-2	0	-1	1	2	-2	0	-1	-2	0	0	0	-1	-1	0	-1	-1	0	-1	0	-1	2	1	3	3	0	0	-1	-1	0
73	-2	3	2	1	3	2	2	-1	-1	-2	-2	2	2	0	3	2	1	0	-1	-1	-1	3	3	2	4	3	2	0	-1	-2
74	2	2	2	1	2	2	-1	-1	-1	0	-2	-1	1	-1	0	1	1	0	-1	-2	-4	4	4	1	3	2	0	0	-1	0
75	-1	1	0	0	0	0	0	0	0	0	-1	-1	-1	-2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
76	0	0	0	0	1	1	1	0	0	0	0	0	1	-1	-1	-1	-1	-1	-1	-1	0	2	2	2	2	2	2	2	-1	-1
77	-2	2	2	4	4	2	3	0	-1	0	-1	-2	0	0	0	0	0	1	0	0	-1	5	2	3	4	0	1	0	-1	0
78	-1	2	2	-1	1	0	-1	-1	-3	-2	-1	0	2	0	1	1	-1	1	0	-2	4	0	5	2	5	3	1	-1	-2	0
79	-2	1	0	-3	0	-1	-2	0	-3	0	-4	-2	0	-5	-2	0	-5	1	-3	0	-3	0	0	2	1	-1	2	-1	0	1
80	1	3	2	-1	0	-1	-2	0	-1	0	-3	0	-1	-1	1	0	-1	1	0	-1	-1	1	-1	0	2	-2	0	-1	-2	-2
81	-2	3	2	1	3	2	2	-2	-1	-1	-3	3	-2	-1	1	0	1	-2	-1	2	-1	4	0	1	4	1	2	0	-1	1
82	-2	0	1	-2	-1	-1	-1	1	-2	-1	2	-2	-1	-3	-1	-1	-3	1	-2	-1	0	0	0	1	0	-1	0	1	-1	-1
83	0	2	2	-2	0	0	0	2	-1	-2	0	0	0	-2	1	-1	-2	0	-2	-2	0	2	1	0	2	1	2	0	0	0
84	-3	0	1	0	3	2	-1	-1	-3	-1	-2	-1	2	0	3	1	1	1	-2	-1	-3	3	1	-1	4	3	2	-1	-2	0
85	0	0	2	2	-1	2	2	3	-2	0	-3	0	0	-3	0	2	0	1	-2	1	0	2	3	0	2	3	0	0	0	1
86	-3	3	4	0	3	3	0	2	-3	-4	-4	2	1	-1	2	2	1	0	0	-1	1	5	4	2	5	4	3	0	-3	-2
87	-2	3	0	0	3	3	1	-1	-2	0	-3	0	0	0	1	0	0	-1	-1	0	-2	2	2	3	4	3	3	-1	0	0
88	-2	1	1	0	2	1	0	0	-1	0	-1	1	0	-1	0	1	-1	0	-1	0	-1	2	2	1	1	1	1	-1	-1	1
89	-3	0	-2	0	0	1	2	-1	0	1	1	-1	-2	-2	-1	0	-1	0	-1	2	0	1	2	2	1	0	1	0	0	2
90	1	4	3	2	3	2	1	0	-1	-2	-1	1	1	0	0	1	-1	1	0	-1	2	4	4	2	4	4	2	1	0	-1
91	1	2	0	1	1	3	2	-1	-2	-1	-1	-1	0	1	1	1	0	1	-1	-2	-1	3	1	2	4	4	3	0	-1	-1
92	-1	2	-2	0	2	1	1	-2	-2	0	-2	1	1	-1	-1	1	-1	1	1	-1	-1	2	1	1	-3	-2	-1	0	0	-1
93	-2	3	0	4	5	1	1	-1	-2	1	-4	0	-1	-3	3	1	1	0	1	-2	-4	1	3	4	4	3	4	1	0	-1
94	-3	3	4	2	4	4	3	3	0	-2	-2	2	2	-2	2	3	2	2	-2	-3	-3	3	4	2	4	4	4	5	0	0
95	-3	3	1	-1	2	0	-1	0	-2	0	-3	2	0	-1	1	0	0	-1	-1	0	-1	2	2	1	3	0	1	-1	-1	0
96	-4	-1	0	-1	1	-2	0	-2	0	1	-3	-4	-4	-5	-4	-1	-2	0	-1	-1	-2	3	2	3	2	2	3	0	0	1
97	-2	0	0	-1	1	2	-1	-3	-3	0	-4	-3	1	-1	0	1	0	2	-2	-1	0	1	2	2	2	2	1	-1	0	-1
98	-3	1	2	0	1	2	-1	1	-1	0	-1	1	0	-2	-1	1	-1	0	-2	-2	-1	3	4	3	2	1	0	1	0	1
99	-2	2	3	0	1	3	0	2	0	-1	0	-1	0	-2	-2	-2	-3	1	-2	-4	0	0	2	0	1	1	1	3	1	0
100	-2	0	1	-2	2	2	-1	-1	-2	-1	0	-2	-1	-3	0	0	-1	1	-1	0	1	0	1	0	2	1	0	-1	-1	0

Appendix VII, c): Descriptive statistics



Description: White Noise (WN), Parts Sound (PS), Pink Noise (PN), Beethoven (B), Eminem (E)

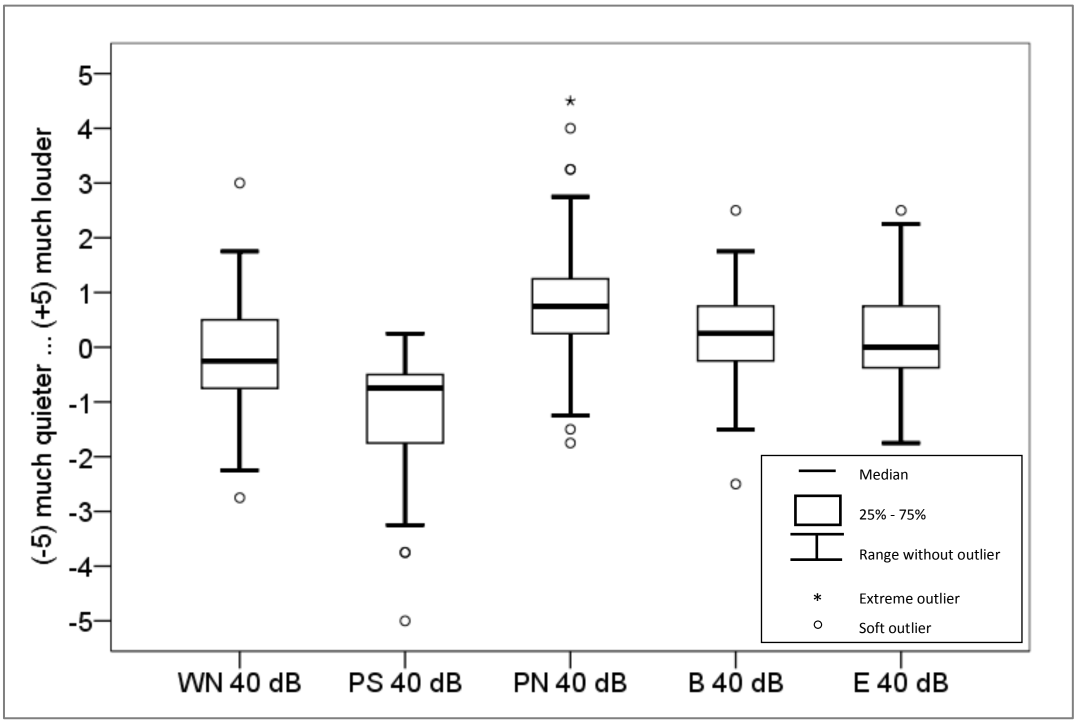
WN Ø vs. PS Ø vs. PN Ø vs. B Ø vs. E Ø

	WN Ø	PS Ø	PN Ø	B Ø	E Ø
Mean	-0.8883	-0.3608	-0.2117	0.4525	1.0083
Standard deviation	0.79598	0.66772	0.70536	0.71561	0.67404
Minimum	-3.67	-2.33	-2.33	-1.25	-0.33
Maximum	0.75	1.50	1.42	3.00	3.00
Median	-0.8333	-0.3333	-0.1667	0.3333	1.0000
N	100	100	100	100	100

<u>Explanation:</u>

The lower the value decreases the more the particular sound of all test persons of all attempts is perceived.
WN is assessed being in total perceived quietest and E loudest.
The perception of PS and PN are in total statistically equal.

Appendix VII, d): Descriptive statistics



Description: White Noise (WN), Parts Sound (PS), Pink Noise (PN), Beethoven (B), Eminem (E)

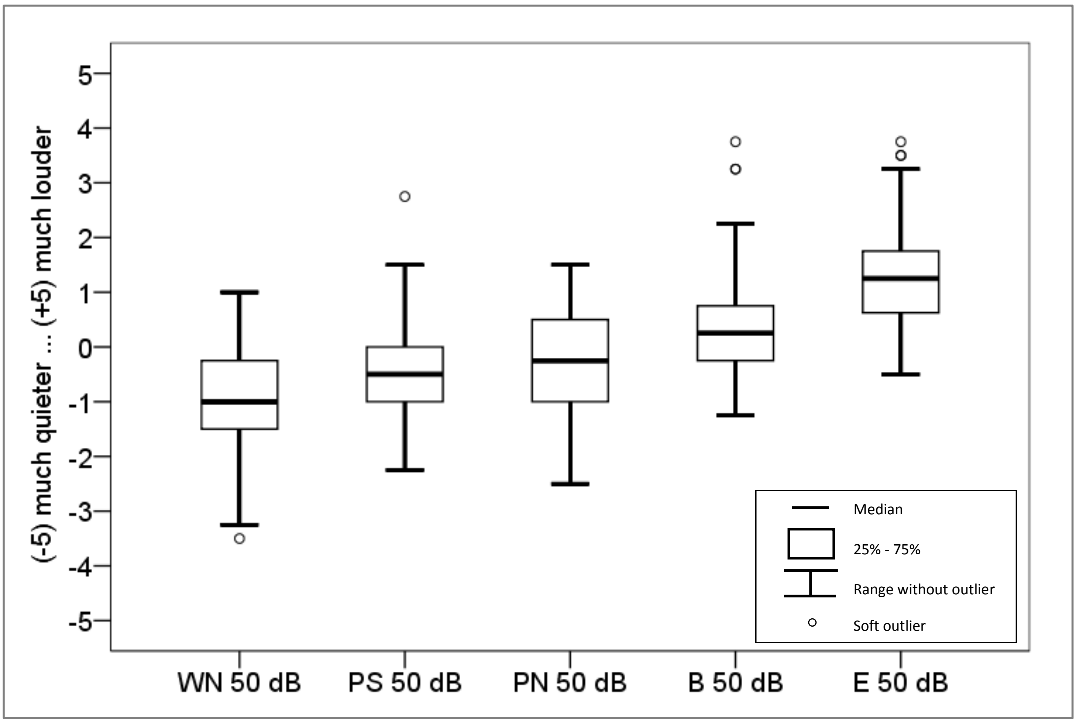
WN 40 dB vs. PS 40 dB vs. PN 40 dB vs. B 40 dB vs. E 40 dB

	WN 40 dB	PS 40 dB	PN 40 dB	B 40 dB	E 40 dB
Mean	-0.1975	-1.1225	0.8775	0.2225	0.2200
Standard deviation	1.01148	0.99525	1.01721	0.79606	0.82211
Minimum	-2.75	-5.00	-1.75	-2.50	-1.75
Maximum	3.00	0.25	4.50	2.50	2.50
Median	-0.2500	-0.7500	0.7500	0.2500	0.0000
N	100	100	100	100	100

Explanation:

At 40 dB PN is judged being perceived loudest and PS quietest.
The perception of E and B is at 40 dB statistically equal.

Appendix VII, e): Descriptive statistics



Description: White Noise (WN), Parts Sound (PS), Pink Noise (PN), Beethoven (B), Eminem (E)

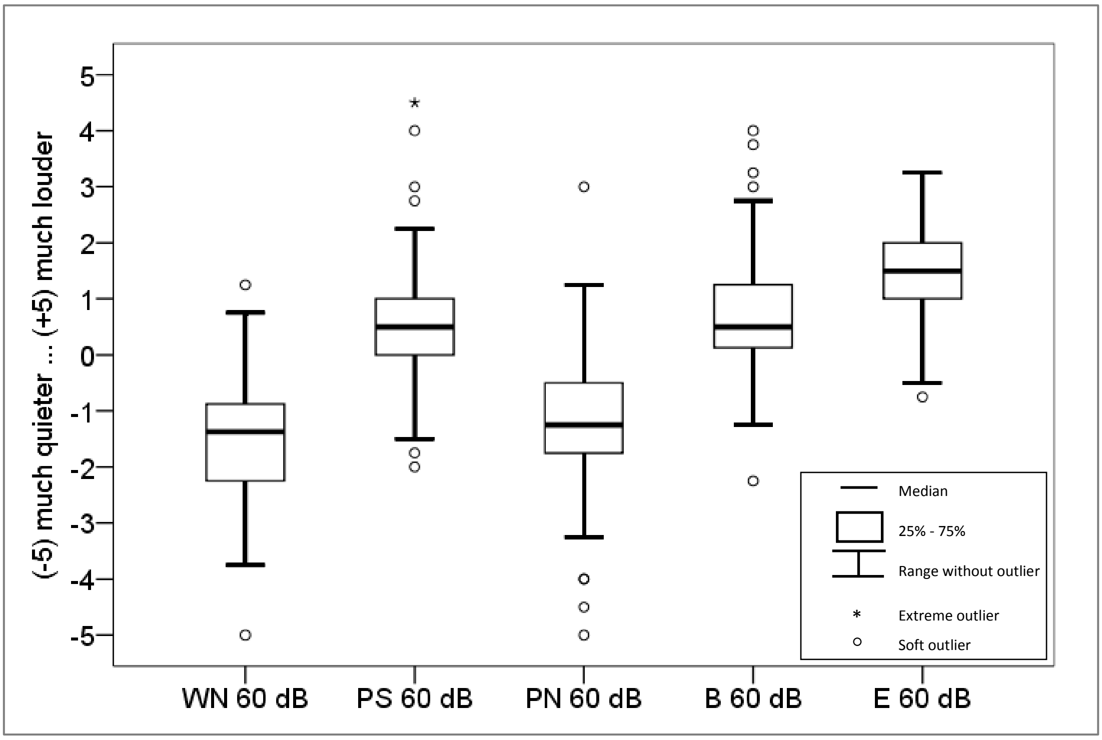
WN 50 dB vs. PS 50 dB vs. PN 50 dB vs. B 50 dB vs. E 50 dB

	WN 50 dB	PS 50 dB	PN 50 dB	B 50 dB	E 50 dB
Mean	-0.9525	-0.4550	-0.2750	0.3750	1.3075
Standard deviation	0.92161	0.85825	0.85834	0.95776	0.89602
Minimum	-3.50	-2.25	-2.50	-1.25	-0.50
Maximum	1.00	2.75	1.50	3.75	3.75
Median	-1.0000	-0.5000	-0.2500	0.2500	1.2500
N	100	100	100	100	100

<u>Explanation:</u>

At 50 dB same order as in total.
The perception of PS and PN is at 50 dB statistically equal.

Appendix VII, f): Descriptive statistics



Description: White Noise (WN), Parts Sound (PS), Pink Noise (PN), Beethoven (B), Eminem (E)

WN 60 dB vs. PS 60 dB vs. PN 60 dB vs. B 60 dB vs. E 60 dB

	WN 60 dB	PS 60 dB	PN 60 dB	B 60 dB	E 60 dB
Mean	-1.5150	0.4950	-1.2375	0.7600	1.4975
Standard deviation	1.04254	1.01627	1.19837	1.01374	0.83673
Minimum	-5.00	-2.00	-5.00	-2.25	-0.75
Maximum	1.25	4.50	3.00	4.00	3.25
Median	-1.3750	0.5000	-1.2500	0.5000	1.5000
N	100	100	100	100	100

<u>Explanation:</u>

At 60 dB PN is perceived relatively quieter than in the total.
WN and PN are judged being perceived quieter than the other.

Appendix VIII, a): Questionnaire, response scale, and results for the 3rd listening test.

For reference see section 5.2.3

Same procedure and equipment as for the 1st Test

Group	L_1 (dB)	R_w=50 dB Type	Test sound L_2 (dB)
1	85	I	B, 85dB (15s)
	85	II	B, 85dB (15s)
	85	III	B, 85dB (15s)
	85	IV	B, 85dB (15s)
	85	V(ref.)	B, 85dB (15s)
2	85	I	E, 85dB (15s)
	85	II	E, 85dB (15s)
	85	III	E, 85dB (15s)
	85	IV	E, 85dB (15s)
	85	V(ref.)	E, 85dB (15s)
3	85	I	PN, 85dB (15s)
	85	II	PN, 85dB (15s)
	85	III	PN, 85dB (15s)
	85	IV	PN, 85dB (15s)
	85	V(ref.)	PN, 85dB (15s)
4	85	I	PS, 85dB (15s)
	85	II	PS, 85dB (15s)
	85	III	PS, 85dB (15s)
	85	IV	PS, 85dB (15s)
	85	V(ref.)	PS, 85dB (15s)
5	85	I	WN, 85dB (15s)
	85	II	WN, 85dB (15s)
	85	III	WN, 85dB (15s)
	85	IV	WN, 85dB (15s)
	85	V(ref.)	WN, 85dB (15s)

Assessment ranking

0	quietest
1	quiet
2	equal
3	loud
4	loudest

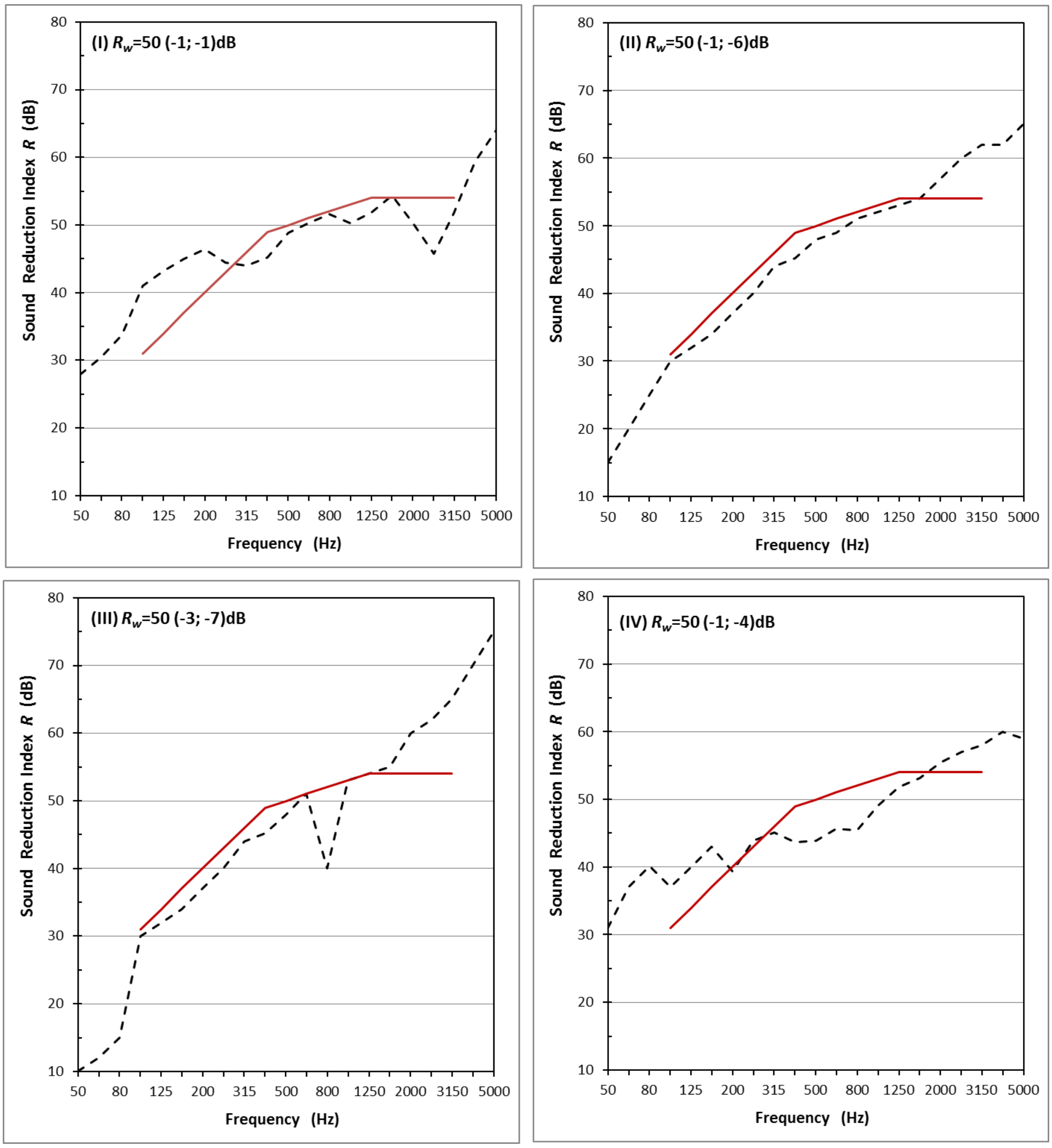
Sound samples

B	Beethoven
E	Eminem
PS	Party Sound
PN	Pink Noise
WN	White Noise

11 Participants

The type: “V(ref.)” represents the shifted reference curve according to ISO 717-1

Appendix VIII, b): Sound reduction index, R_w = 50 dB with different C, C_{tr}-values.



The response sheet is given in Appendix VIII, c).

The reference values for V(Ref-curve) in Appendix VIII, c), are the shifted reference values of the reference curve according to ISO 717-1. Reference value: $R_{w,ref}$ = 50 (-2; -6) dB.

Appendix VIII, c): Response sheet.

I	II	III	IV	V (Ref-curve)
R_w=50 (-1; -1)dB	R_w=50 (-1; -6)dB	R_w=50 (-3; -7)dB	R_w=50 (-1; -4)dB	R_w=50 (-2; -6)dB

0 'quietest' 1 'quiet' 2 'equal' 3 'loud' 4 'loudest'

Participant 1	B	E	PS	PN	WN
I	3	4	2	4	4
II	2	1	1	1	1
III	0	0	0	0	0
IV	4	2	3	2	2
V(ref)	1	3	4	3	3

Participant 2	B	E	PS	PN	WN
I	3	3	2	2	2
II	0	1	0	1	1
III	1	0	1	0	0
IV	4	2	3	3	3
V(ref)	2	4	4	4	4

Participant 3	B	E	PS	PN	WN
I	4	3	3	4	2
II	0	0	1	1	1
III	1	1	0	0	0
IV	3	4	4	3	3
V(ref)	2	2	2	2	4

Participant 4	B	E	PS	PN	WN
I	3	4	2	4	4
II	2	1	1	1	1
III	0	0	0	0	0
IV	4	2	3	2	2
V(ref)	1	3	4	3	3

Participant 5	B	E	PS	PN	WN
I	2	2	2	2	3
II	1	1	1	1	1
III	0	0	0	0	0
IV	4	4	3	3	2
V(ref)	3	3	4	4	4

Participant 6	B	E	PS	PN	WN
I	1	3	4	1	2
II	0	0	1	2	1
III	2	1	0	0	0
IV	4	4	3	3	3
V(ref)	3	2	2	4	4

Participant 7	B	E	PS	PN	WN
I	2	1	3	2	2
II	1	0	1	1	1
III	0	3	0	0	0
IV	4	2	3	3	4
V(ref)	3	4	4	4	3

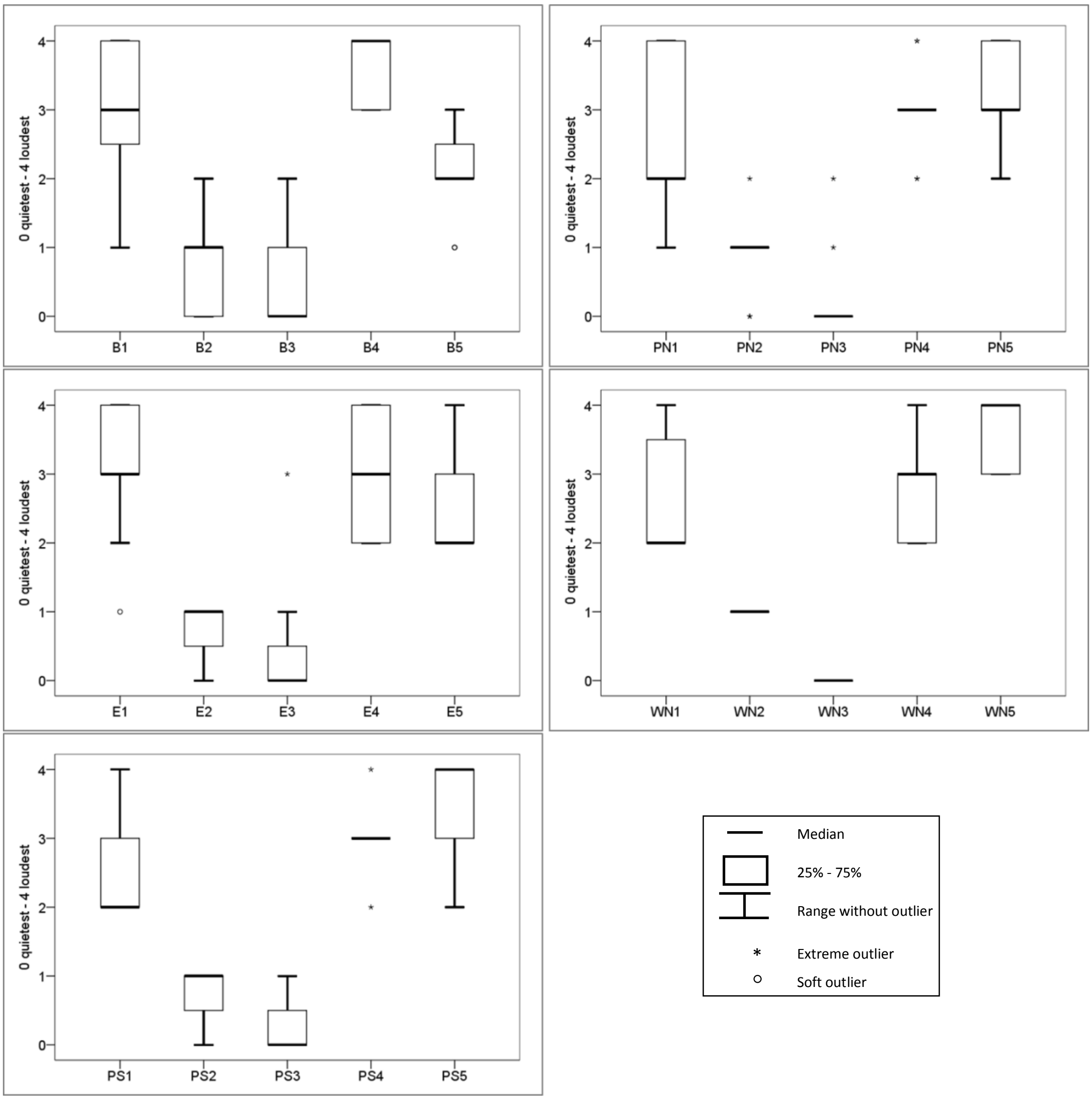
Participant 8	B	E	PS	PN	WN
I	4	4	4	4	2
II	1	1	1	0	1
III	0	0	0	1	0
IV	3	3	3	3	3
V(ref)	2	2	2	2	4

Participant 9	B	E	PS	PN	WN
I	4	3	2	1	2
II	1	1	0	0	1
III	0	0	1	2	0
IV	3	4	3	4	3
V(ref)	2	2	4	3	4

Participant 10	B	E	PS	PN	WN
I	4	3	3	2	4
II	0	1	1	1	1
III	1	0	0	0	0
IV	3	4	2	4	2
V(ref)	2	2	4	3	3

Participant 11	B	E	PS	PN	WN
I	4	4	2	2	2
II	0	1	0	1	1
III	1	0	1	0	0
IV	3	3	3	3	3
V(ref)	2	2	4	4	4

Appendix VIII, d): Results of the 3rd listening test shown in a Boxplot.



The numbers 1 – 5 refer to the filter types *I* – *V* (i.e. sound reduction index R_w = 50 (C; Ctr)), for example, B1 refers to the sound sample Beethoven filtered with filter type *I*.

Appendix VIII, e): Results of the significant test for the 3rd listening test.

All **bold** significance values show a significant difference between the two sounds = at sign. < 0.05
All thin significance values show that two sounds are statistically perceived equal = at sign. > 0.05

Significance-Values Wilcoxon Test					
All	**I**	**II**	**III**	**IV**	**V**
Mean	2.80	0.82	0.31	3.07	3.02
I		**0.003**	**0.003**	0.228	0.448
II			**0.004**	**0.003**	**0.003**
III				**0.003**	**0.003**
IV					0.788
V					
B	**B1**	**B2**	**B3**	**B4**	**B5**
Mean	3.09	0.73	0.55	3.55	2.09
B1		**0.003**	**0.004**	0.329	0.045
B2			0.642	**0.003**	0.011
B3				**0.003**	**0.003**
B4					**0.002**
B5					
E	**E1**	**E2**	**E3**	**E4**	**E5**
Mean	3.09	0.73	0.45	3.09	2.64
E1		**0.003**	**0.006**	0.963	0.227
E2			0.285	**0.003**	**0.003**
E3				**0.004**	**0.003**
E4					0.361
E5					
PS	**PS1**	**PS2**	**PS3**	**PS4**	**PS5**
Mean	2.64	0.73	0.27	3.00	3.45
PS1		**0.003**	**0.003**	0.206	0.137
PS2			0.132	**0.003**	**0.003**
PS3				**0.003**	**0.003**
PS4					0.236
PS5					
PN	**PN1**	**PN2**	**PN3**	**PN4**	**PN5**
Mean	2.55	0.91	0.27	3.00	3.27
PN1		**0.008**	**0.005**	0.413	0.169
PN2			0.097*)	**0.003**	**0.003**
PN3				**0.003**	**0.003**
PN4					0.366
PN5					
WN	**WN1**	**WN2**	**WN3**	**WN4**	**WN5**
Mean	2.64	1.00	0.00	2.73	3.64
WN1		**0.002**	**0.002**	0.963	0.028
WN2			**0.001**	**0.003**	**0.002**
WN3				**0.003**	**0.002**
WN4					**0.008**
WN5					

*) tends to be significant

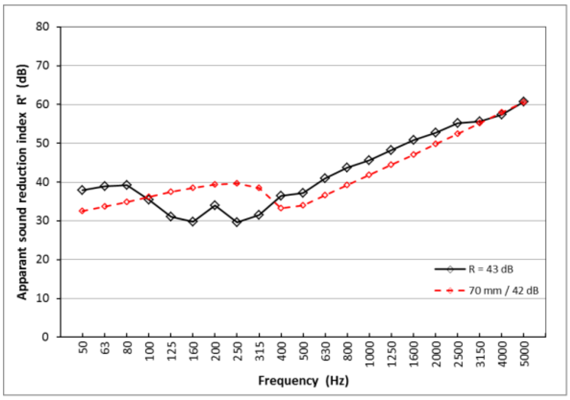
Appendix IX, a): Measured and calculated *R*-, and R_w-values, and related values.

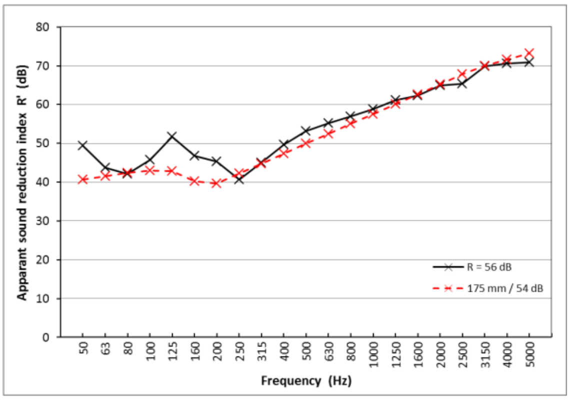
Material: Sand-lime brick, Thickness t = 70/115/150/175/240/300 mm; Signal: pink noise

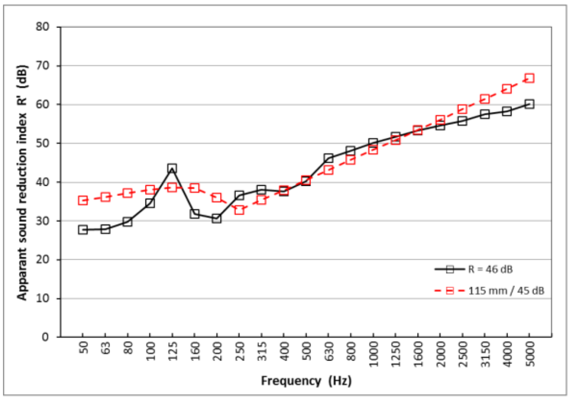
Sound reduction index (*R*) in dB												
f	**70 mm**		**115 mm**		**150 mm**		**175 mm**		**240 mm**		**300 mm**	
Hz	Meas.	Calc.	Meas.	Calc.	Meas.	Calc.	Meas.	Calc.	Meas.	Calc.	Meas.	Calc.
50	37.9	32.6	27.7	35.3	43.6	39.2	49.4	40.7	53.5	43.6	55.0	46.0
63	39.0	33.7	27.9	36.2	38.2	40.2	43.8	41.6	46.4	44.3	48.2	46.7
80	39.2	34.9	29.8	37.2	48.7	41.1	42.2	42.4	44.6	44.9	45.1	47.1
100	35.5	36.2	34.6	38.1	36.5	41.8	45.8	43.0	45.6	44.7	50.7	45.5
125	31.0	37.4	43.5	38.7	43.8	42.0	51.7	42.8	46.4	42.1	51.4	44.5
160	29.8	38.5	31.9	38.5	40.6	41.0	46.7	40.3	43.8	42.8	46.8	47.0
200	34.0	39.3	30.6	36.0	43.0	37.8	45.3	39.7	46.3	45.3	50.5	49.5
250	29.6	39.6	36.6	32.8	42.4	39.3	40.7	42.2	48.2	47.8	48.4	52.0
315	31.5	38.5	38.1	35.4	43.4	41.9	45.1	44.8	52.0	50.3	52.7	54.5
400	36.5	33.3	37.7	37.9	45.9	44.4	49.7	47.3	52.5	52.9	57.1	57.1
500	37.2	34.0	40.3	40.5	50.4	47.0	53.1	49.9	56.4	55.4	62.0	59.6
630	41.0	36.6	46.2	43.1	54.1	49.5	55.1	52.4	58.9	57.9	62.9	62.1
800	43.7	39.2	48.0	45.7	54.4	52.1	56.9	55.0	61.3	60.5	64.1	64.6
1000	45.6	41.8	50.1	48.3	55.9	54.7	58.8	57.5	63.1	63.0	66.1	67.2
1250	48.2	44.5	51.7	50.9	58.6	57.2	61.1	60.1	64.6	65.6	68.1	69.4
1600	50.8	47.1	53.2	53.5	60.3	59.8	62.3	62.6	65.8	68.1	69.6	71.0
2000	52.7	49.8	54.6	56.1	62.3	62.4	64.9	65.2	68.2	70.0	72.1	72.5
2500	55.2	52.5	55.8	58.8	63.7	65.0	65.3	67.8	69.1	71.5	73.2	74.1
3150	55.6	55.2	57.6	61.4	66.0	67.6	69.8	70.0	70.7	73.1	75.2	75.6
4000	57.4	57.9	58.2	64.1	69.9	70.0	70.6	71.6	71.8	74.7	75.4	77.2
5000	60.8	60.6	60.1	66.8	70.4	71.6	70.8	73.2	66.7	76.3	70.8	78.8
R_w (dB)	**43**	42	**46**	45	**54**	51	**56**	54	**60**	59	**63**	63
C (dB)	-1	1-	-1	0	-1	0	-1	-1	-1	-1	-2	-1
C_{tr} (dB)	-5	-3	-4	-3	-5	-4	-5	-5	-5	-5	-5	-6
m' (kg/m²)	130		180		285		341		475		614	
f_c (Hz)	423		237		200		173		127		104	
L_{nor} (-)	1.029		0.969		1.057		1.064		1.025		1.018	
w (-)	1.047		0.996		0.889		0.858		0.841		0.889	
$L_{nor,w}$ (-)	**1.078**		**0.964**		**0.940**		**0.912**		**0.862**		**0.905**	

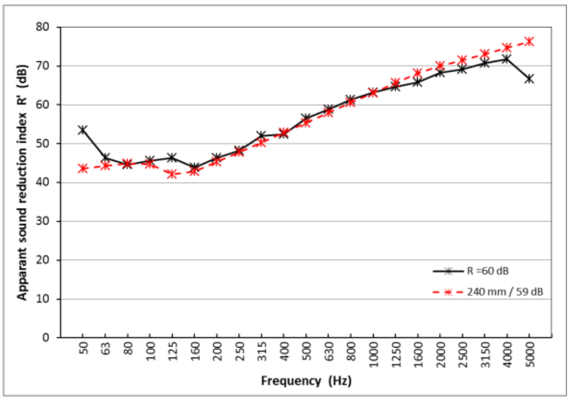
Appendix IX, b): Measured and calculated *R*-, and R_w-values for comparison.

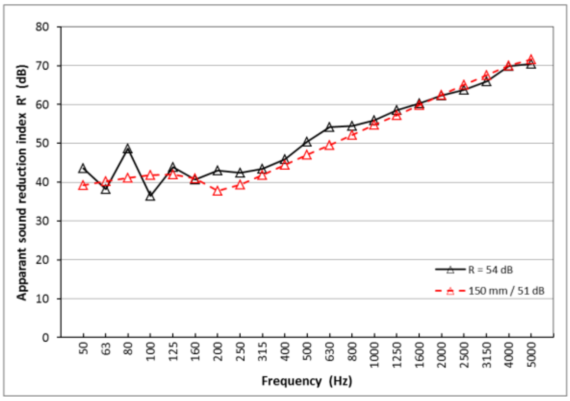
Material: Sand-lime brick, Thickness t = 70/115/150/175/240/300 mm

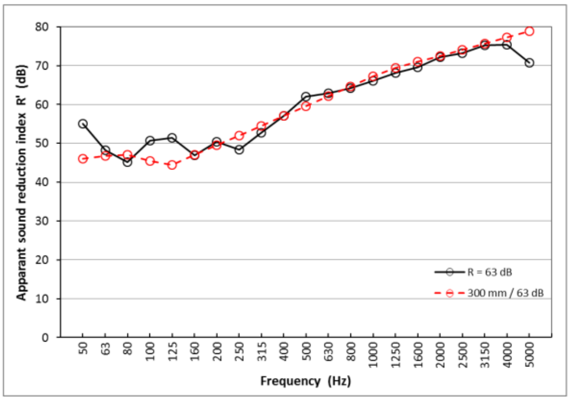








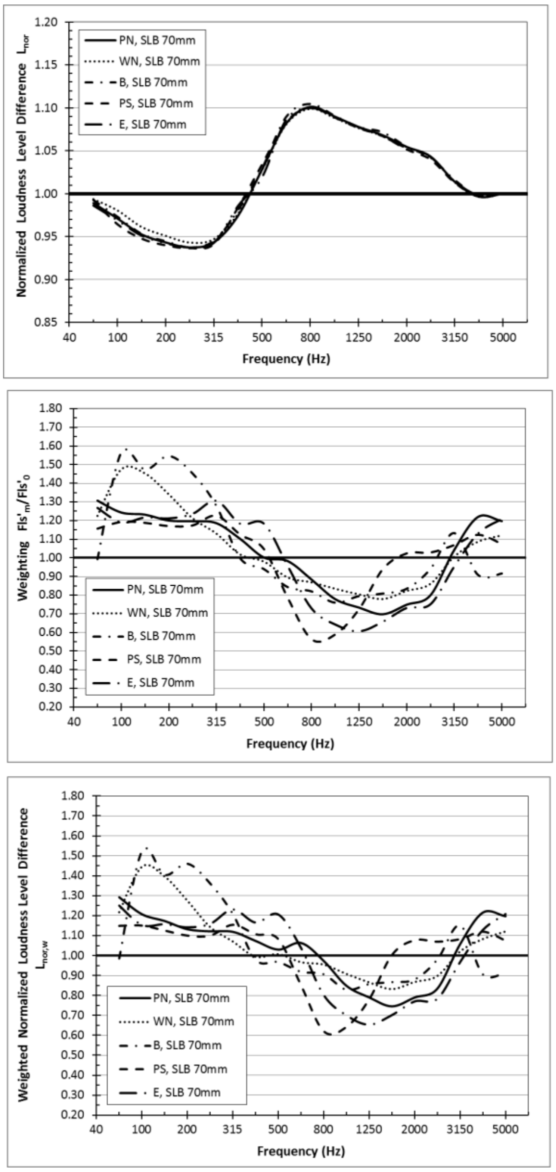




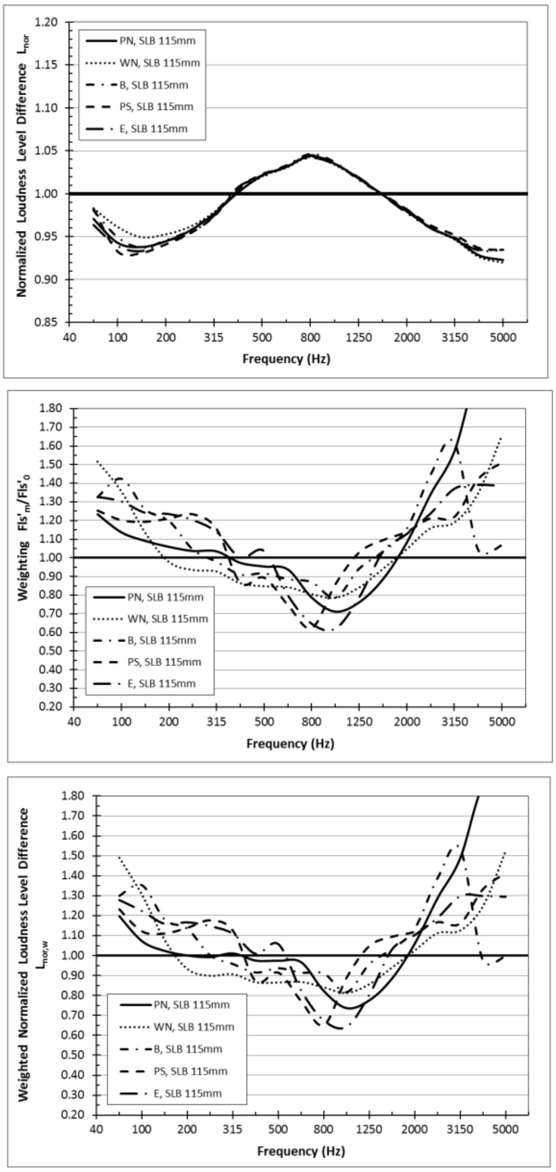
Black solid line shows the laboratory measurement results and the red dotted line shows calculated values.

Appendix IX, c): Calculated frequency depending values using Eqs. (4-6), (4-8), and (4-10).

Material: Sand-lime brick (SLB), Thickness t = 70/115/150/175/240/300 mm



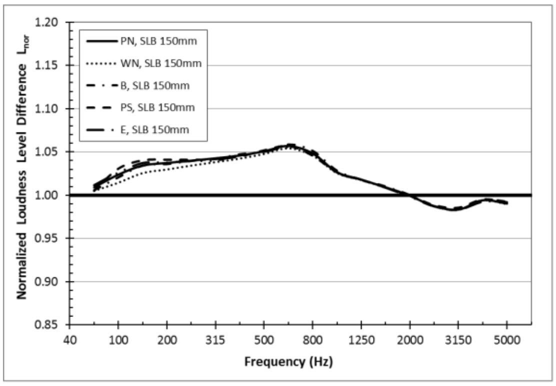
SLB d = 70 mm, R_w=43 (-1; -5) dB

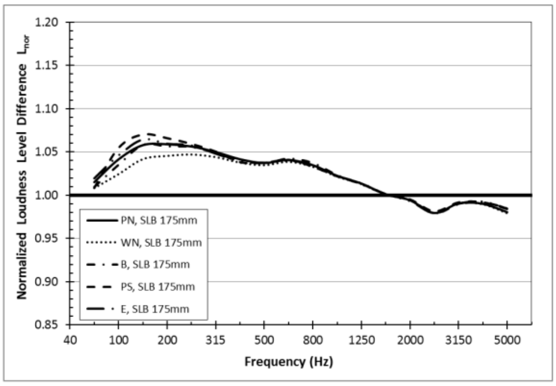


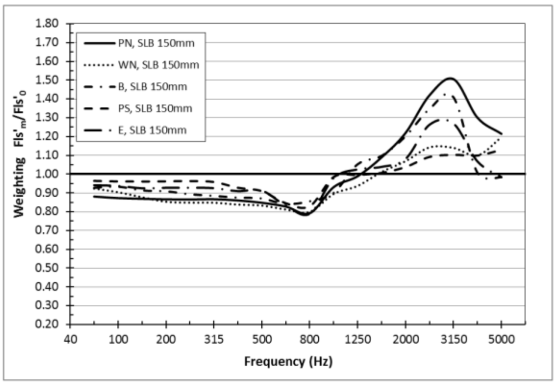
SLB d = 115 mm, R_w=46 (-1; -4) dB

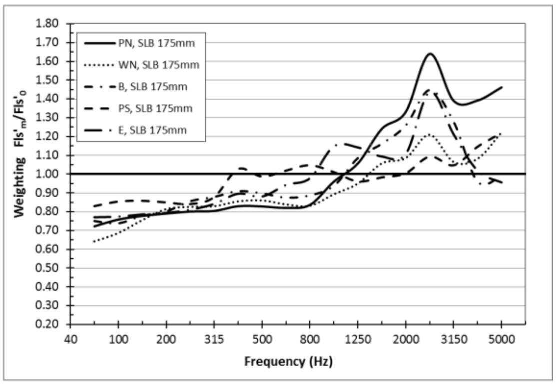
Appendix IX, d): Calculated frequency depending values using Eqs. (4-6), (4-8), and (4-10).

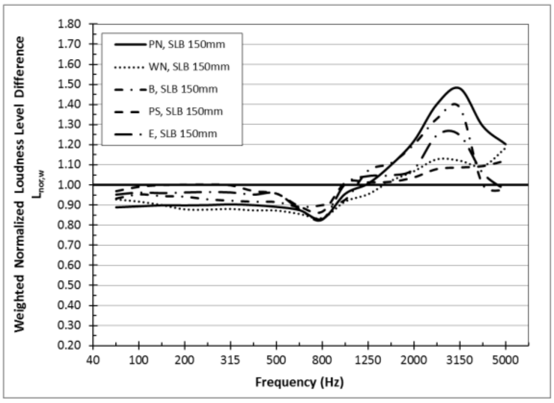
Material: Sand-lime brick (SLB), Thickness t = 70/115/150/175/240/300 mm

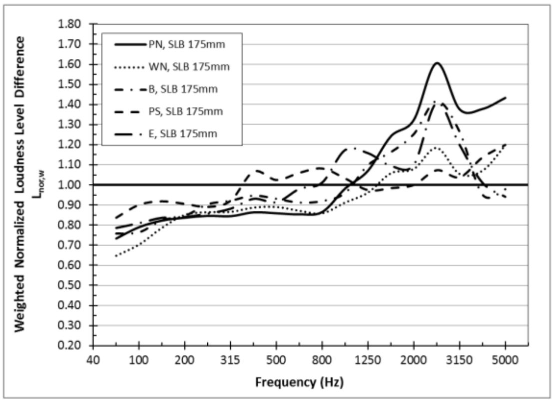










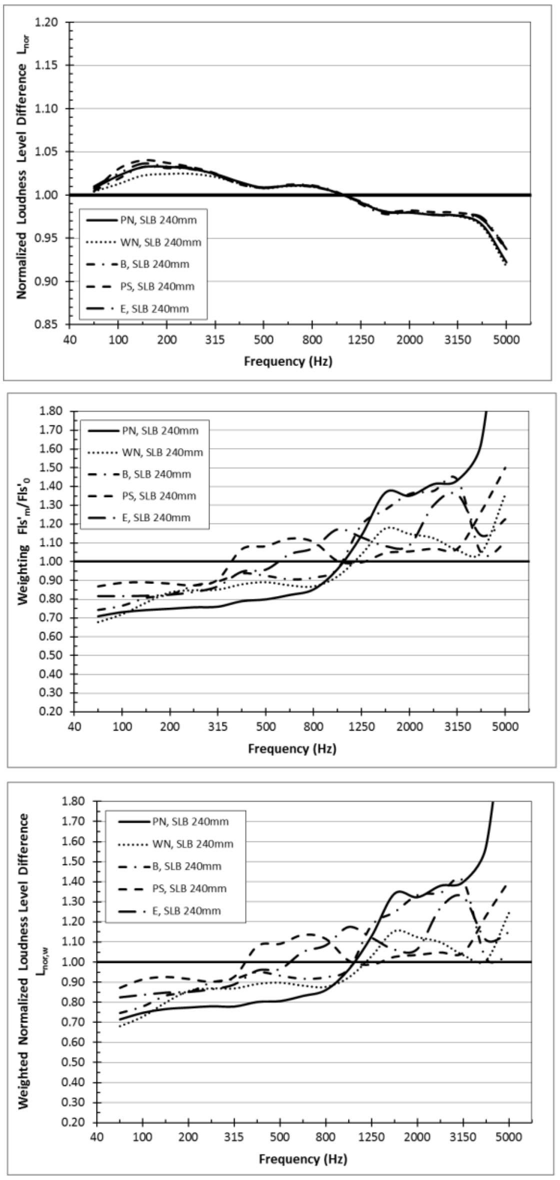


SLB d = 150 mm, R_w=54 (-1; -5) dB

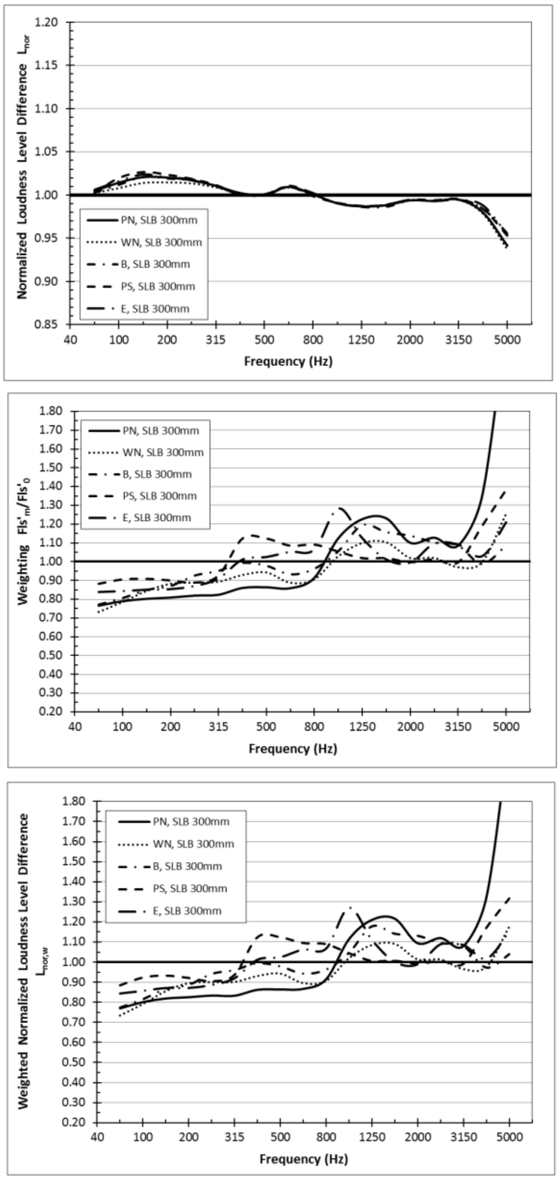
SLB d = 175 mm, R_w=56 (-1; -5) dB

Appendix IX, e): Calculated frequency depending values using Eqs. (4-6), (4-8), and (4-10).

Material: Sand-lime brick (SLB), Thickness t = 70/115/150/175/240/300 mm



SLB d = 240 mm, R_w=60 (-1; -5) dB



SLB d = 300 mm, R_w=63 (-2; -5) dB

Appendix X: Instrument set-up to carry out the transmission loss measurements

Airborne sound insulation measurements (transmission loss measurements):

— 2-channel real time analyser, Norsonic, Type 840-2, serial number 17837

— 1/2-condenser microphone, Norsonic, Type 1220, serial number 15500
  with preamplifier, Norsonic, Type 1201, serial number 18131

— 1/2-condenser microphone, Norsonic, Type 1220, serial number 16354
  with preamplifier, Norsonic, Type 1201, serial number 18132

— Loudspeaker (Dodecahedron), Norsonic, Type 229, serial number 31065
  Amplifier type 235, Norsonic, serial number 17679

— Acoustic calibrator class 1, Type 1251, Norsonic, serial number 17383

Appendix XI: Calculated R_w-, corresponding Ref.-values (ISO 717-1), and related values.

Material: Concrete, Thickness t = 100 mm - 400 mm; Signal: pink noise

	Sound reduction index (*R*) in dB													
f	**100 mm**		**150 mm**		**200 mm**		**250 mm**		**300 mm**		**350 mm**		**400 mm**	
Hz		Ref.		Ref.		Ref.		Ref.		Ref.		Ref.		Ref.
50	37.7	30	41.1	35	43.6	40	45.6	43	47.4	46	49.3	48	51.1	50
63	38.7	30	42.1	35	44.4	40	46.4	43	48.3	46	50.2	48	52.2	50
80	39.9	30	43.0	35	45.2	40	47.0	43	48.9	46	48.5	48	47.6	50
100	41.0	30	43.8	35	45.6	40	47.1	43	46.2	46	46.6	48	48.9	50
125	41.9	33	44.2	38	45.1	43	44.2	46	46.5	49	49.1	51	51.4	53
160	42.6	36	43.5	41	42.7	46	45.9	49	49.0	52	51.6	54	53.9	56
200	42.6	39	40.8	44	44.6	49	48.4	52	51.5	55	54.2	57	56.5	59
250	40.6	42	42.3	47	47.1	52	50.9	55	54.0	58	56.7	60	59.0	62
315	38.1	45	44.8	50	49.7	55	53.5	58	56.6	61	59.2	63	61.5	65
400	40.7	48	47.4	53	52.2	58	56.0	61	59.1	64	61.7	66	64.0	68
500	43.3	49	50.0	54	54.8	59	58.6	62	61.7	65	64.2	67	65.9	69
630	45.9	50	52.6	55	57.4	60	61.1	63	63.9	66	65.8	68	67.5	70
800	48.5	51	55.1	56	59.9	61	63.2	64	65.4	67	67.3	69	69.0	71
1000	51.1	52	57.7	57	62.0	62	64.7	65	67.0	68	68.9	70	70.6	72
1250	53.8	53	60.1	58	63.6	63	66.3	66	68.5	69	70.4	71	72.1	73
1600	56.4	53	61.8	58	65.2	63	67.9	66	70.1	69	72.0	71	73.7	73
2000	58.8	53	63.4	58	66.8	63	69.5	66	71.7	69	73.6	71	75.2	73
2500	60.5	53	65.0	58	68.4	63	71.1	66	73.3	69	75.1	71	76.8	73
3150	62.2	53	66.7	58	70.0	63	72.7	66	74.8	69	76.7	71	78.4	73
4000	63.9	53	68.4	58	71.7	63	74.3	66	76.4	69	78.3	71	79.9	73
5000	65.6	53	70.0	58	73.3	63	75.9	66	78.1	69	79.9	71	81.5	73
R_w (dB)	**49**		**54**		**59**		**62**		**65**		**67**		**69**	
C (dB)	-1		-1		-2		-2		-2		-2		-2	
C_{tr} (dB)	-3		-4		-5		-5		-6		-6		-6	
m' (kg/m²)	234		351		468		585		702		819		936	
f_c (Hz)	299		199		150		120		100		85		75	
L_{nor} (-)	1.073		1.059		0.994		0.978		0.956		0.958		0.962	
w (-)	1.219		1.221		1.248		1.230		1.229		1.216		1.201	
***$L_{nor,w}$* (-)**	**1.308**		**1.293**		**1.242**		**1.205**		**1.175**		**1.164**		**1.155**	

Detailed calculation results for different thicknesses of concrete.

Appendix XII: Discrimination of $L_{nor,w}$ for different conditions of L_N and *Fls'*

Region	Condition			Sound reduction index	Signal	Construction Concrete t (mm)
I	$L_{2,m} < L_{2,0}$:	$L_{nor} > 1$	$L_{nor,w} > 1$	R_w = 65 (-2; -6) dB	PN, WN	300
	$Fls_{,m} > Fls_{,0}$:	$w > 1$				
II	$L_{2,m} > L_{2,0}$:	$L_{nor} < 1$	$L_{nor,w} < 1$	R_w = 54 (-1; -4) dB	PS	150
	$Fls_{2,m} < Fls_{,0}$:	$w < 1$				
III	$L_{2,m} < L_{2,0}$:	$L_{nor} > 1$	$L_{nor,w} < 1$	R_w = 49 (-1; -3) dB	PS	100
	$Fls_{,m} < Fls_{,0}$:	$w < 1$		R_w = 50 (-1; -3) dB	PS	110
				R_w = 50 (-1; -1) dB	PN	-
IV	$L_{2,m} > L_{2,0}$:	$L_{nor} < 1$	$L_{nor,w} < 1$	R_w = 59 (-2; -5) dB	PN, B, E	200
	$Fls_{,m} > Fls_{,0}$:	$w > 1$		R_w = 65 (-2; -6) dB	PN	300
V	$L_{2,m} > L_{2,0}$:	$L_{nor} < 1$	$L_{nor,w} > 1$	R_w = 69 (-2; -6) dB	PN, E, PS	400
	$Fls_{,m} > Fls_{,0}$:	$w > 1$				
VI	$L_{2,m} < L_{2,0}$:	$L_{nor} > 1$	$L_{nor,w} > 1$	R_w = 50 (-1; -1) dB	WN, B	-
	$Fls_{,m} > Fls_{,0}$:	$w < 1$				

Constructions fulfilling R_w (C; C_{tr}) for different sound signals.

Appendix XIII, a): R_w = 50 (C; C_{tr}) dB. Calculated L_{nor}-, $L_{nor,w}$-values. Signal: pink noise.

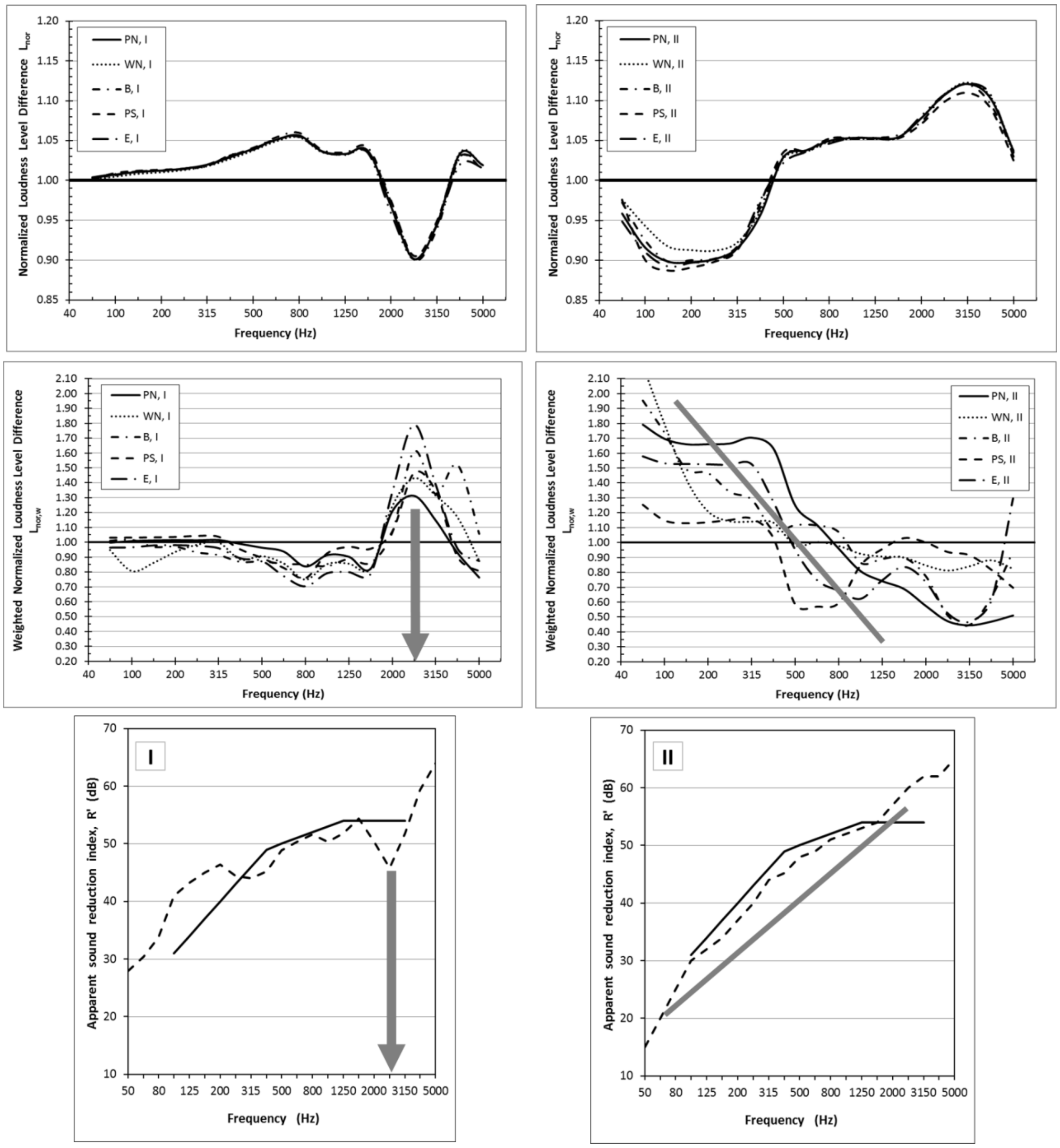
(Refer to Appendix VIII b)

	Sound reduction index (R_w) in dB				
f (Hz)	**I**	**II**	**III**	**IV**	**Ref.**
50	27.9	15.0	10.0	31.0	22
63	30.4	20.0	12.0	37.0	25
80	33.8	25.0	15.0	40.1	28
100	41.0	30.0	30.0	37.0	31
125	43.2	32.0	32.0	40.0	34
160	45.0	34.0	34.0	43.0	37
200	46.4	37.0	37.0	39.4	40
250	44.4	40.0	40.0	43.9	43
315	44.0	44.0	44.0	45.1	46
400	45.2	45.2	45.2	43.7	49
500	48.9	48.0	48.0	43.9	50
630	50.3	49.0	51.0	45.6	51
800	51.6	51.0	40.0	45.4	52
1000	50.3	52.0	53.0	49.1	53
1250	51.8	53.0	54.0	51.8	54
1600	54.4	54.0	55.0	53.1	54
2000	50.3	57.0	60.0	55.5	54
2500	45.8	60.0	62.0	57.0	54
3150	51.8	62.0	65.0	58.0	54
4000	59.3	62.0	70.0	60.0	54
5000	64.0	65.0	75.0	59.0	54
R_w (dB)	**50**	**50**	**50**	**50**	50
C (dB)	-1	-1	-3	-1	-2
C_{tr} (dB)	-1	-6	-7	-4	-6
L_{nor} (-)	1.092	1.010	0.985	1.006	-
w (-)	0.987	1.215	1.279	0.969	-
$L_{nor,w}$ (-)	**0.975**	**1.227**	**1.260**	**0.974**	**-**

Different $L_{nor,w}$-values for group samples (*I – IV*), signal pink noise filtered with R_w = 50 dB but different *C*-, C_{tr}-values. “Ref.” indicates the shifted reference curve according ISO 717-1.

Appendix XIII, b): Calculated R_w-values yielding R_w = 50 dB. Different signals. Case I + II

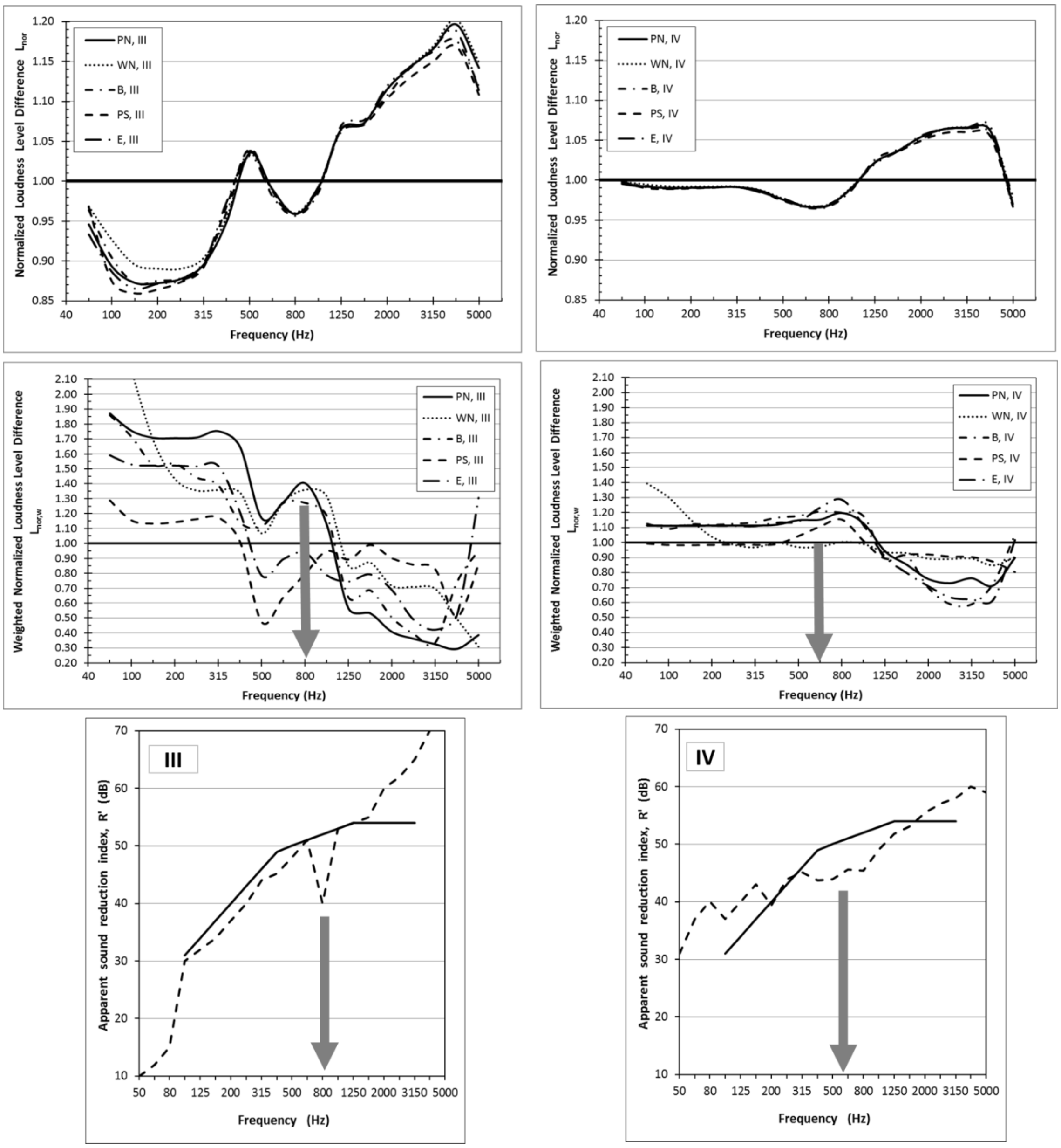
(Refer to Appendix VIII b)



Die grey arrow indicates the frequency dip on the frequency axis. In the right panel the grey bar indicates the overall frequency response.

Appendix XIII, c): Calculated R_w-values yielding R_w = 50 dB. Different signals. Case III + IV

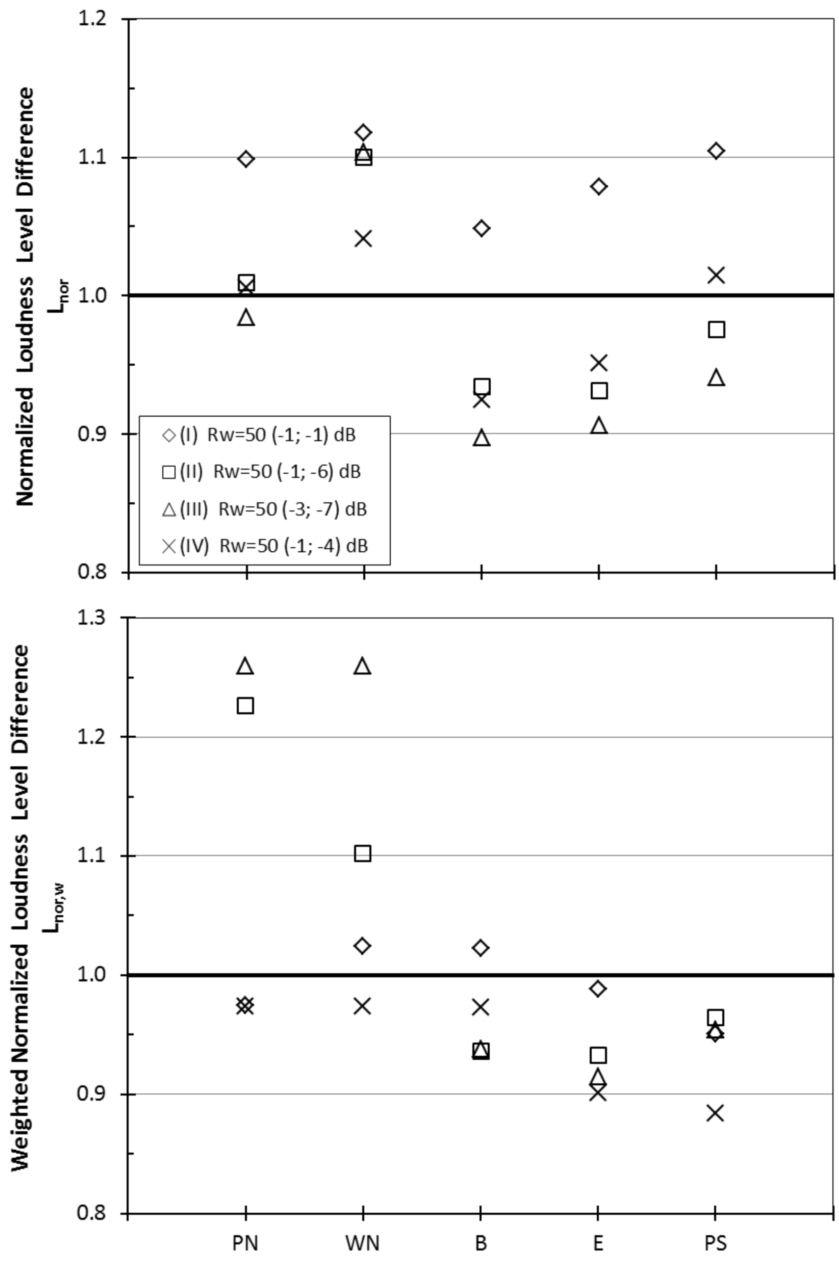
(Refer to Appendix VIII b)



Die grey arrow indicates the frequency dip on the frequency axis.

Appendix XIII, d): Calculated R_w-values yielding R_w = 50 dB. Different signals.

(Refer to Appendix VIII b)

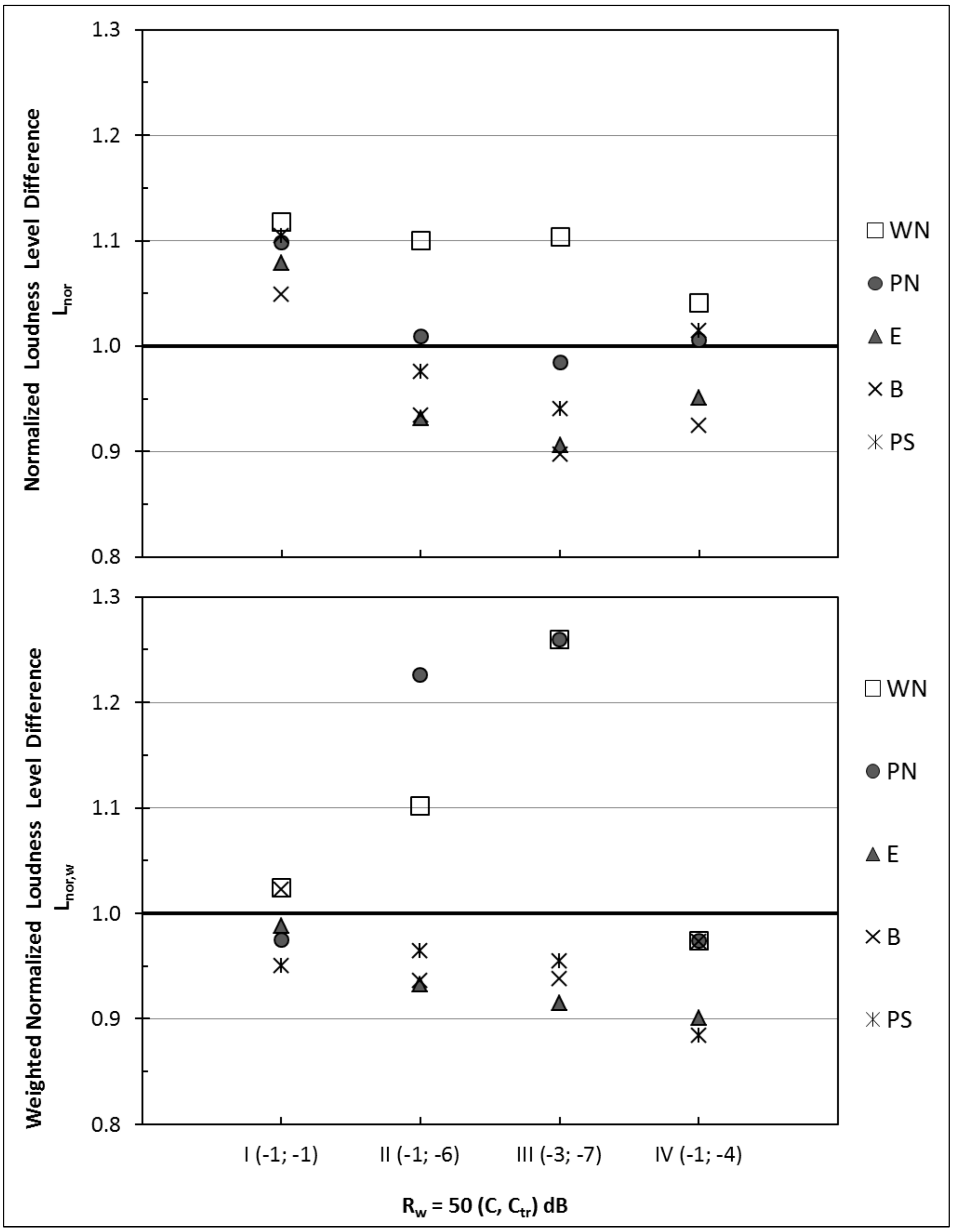


Different sound samples filtered with R_w = 50 dB but different C-, C_{tr}-values.

Results grouped in same sound sample group (PN, WN, B, E, PS).

Appendix XIII, e): Calculated R_w-values yielding R_w = 50 dB. Different signals.

(Refer to Appendix VIII b)



Different sound samples filtered with R_w = 50 dB but different *C*-, C_{tr}-values.

Results grouped in same construction group (*I – IV*).

PUBLICATIONS

The thesis is based on the work contained in the following papers:

Neubauer, R. O. (**2015**). COST Action TU0901 – Harmonisierung von Kennwerten und Klassifikationschema für den baulichen Schallschutz – Eine Zusammenfassung der Ergebnisse, (Harmonisation of descriptors and classification scheme for the structural sound protection - A summary of the results), (in German). Proceedings in Fortschritte der Akustik, DAGA 2015, Nuremberg, Germany. (Invited paper)

Neubauer, R. O., Kang, J. (**2014 a**). Airborne sound insulation in terms of a loudness model. *Journal of Applied Acoustics*, **85**, 34-45.

Neubauer, R. O., Kang, J. (**2014 b**). Airborne Sound Insulation Based on a Model of Loudness. Proc. 21st International Congress on Sound and Vibration (ICSV), Beijing, China. (Refereed).

Neubauer, R. O., Kang, J. (**2014 c**). A Model Based on Loudness Level to Describe Airborne Sound Insulation. Proceedings of the 43rd International Congress on Noise Control Engineering (InterNoise), Melbourne, Australia. (Refereed).

Neubauer, R. O., Kang, J. (**2013 a**). Subjective Evaluation of Airborne Sound Insulation below 100 Hz. Proceedings of the 40th Italian Annual Conference on Acoustics (AIA), 39th German Annual Conference on Acoustics (DAGA), combined with European Acoustics Association (EAA) Euroregio, Merano, Italy. (Refereed).

Neubauer, R. O., Kang, J. (**2013 b**). Airborne sound insulation as a measure for noise annoyance. Proceedings of the 21st International Congress on Acoustics, joint with the 165th Meeting of the Acoustical Society of America and 52nd Meeting of the Canadian Acoustical Association, Montréal, Québec, Canada. (Refereed).

Neubauer, R. O., Kang, J. (**2012 a**). "Rating Airborne Sound Insulation in Terms of Time Structure of the Signal". Proceedings of the 41st International Congress and Exposition on Noise Control Engineering (InterNoise), New York City, USA.

Neubauer, R. O., Kang, J. (**2012 b**). "Time Structure Of The Signal In Airborne Sound Insulation". Proceedings of the 9th European Conference on Noise Control (EuroNoise), Prague, Czech Republic.

Neubauer, R. O., Kang, J. (**2011 a**). "What Describes the Airborne Sound Insulation in Technical and Subjective Regard?" Proceedings of the 6th Forum Acusticum, Aalborg, Denmark, ISSN 2221-3767, 1783-1787. (Invited paper).

Neubauer, R. O., Kang, J. (**2011 b**). "Temporal aspects of airborne sound insulation and how it affects the subjective estimation". The 5th International Symposium on Temporal Design, Sheffield, United Kingdom. (Invited paper).