Aalborg University

Master's Thesis

Acoustic Indoor Comfort of Modern Dwellings

Author:
Mikkel Krogh Simonsen
Kasper Kiis Jensen

Group:
18gr1061

Supervisor:
Flemming Christensen

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STUDENT REPORT

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Institute of Electronic Systems
Fredrik Bajers Vej 7
DK-9220 Aalborg Ø

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Kasper Kiis Jensen
Mikkel Krogh Simonsen

Supervisor:
Flemming Christensen

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Abstract:

Throughout the years indoor acoustics have worsened and received little focus. This project has covered the subject of acoustic indoor comfort in dwellings with the purpose of proposing a classification for acoustic comfort. The project covers current standards and regulations. It has analysed current standardized parameters for describing sound in rooms. A measurement program was developed to create a database of room impulses measured complying with ISO 3382-2 in actual dwellings. A questionnaire was developed to obtain subjective data from the residents. 45 rooms were measured throughout 15 dwellings along with 15 answered questionnaires. The data was analysed using multiple factor analysis. The standardized room acoustical parameters showed high redundancies. The objective data showed a stronger correlation with absorption in a room compared to reverberation when rating acoustic satisfaction which is not noted in the current standards. A larger database must be collected to if acoustic comfort is to be classified.

Contents

Preface

This report has been carried out during spring of 2018 as a 4th semester Acoustics and Audio Technology student master project at Aalborg University by group 18gr1061. The project concerns classification of acoustical comfort inside dwellings. The project was made partly in cooperation with the research project REBUS [Larsen et al., 2017] and in conjunction with REBUS the measurement program described in this report was developed by the authors.

The figures in this report are produced by the authors unless a source is specified. Sources are indicated by [author,year] and can be found in the bibliography. All quantities and units are displayed conforming with [ISO 80000-8, 2007]. The report is divided into a main report and an appendix with each structured in chapters and sections. Every figure, table, equation and listing is separately numbered continuously through every chapter. Figures can be diagrams, flowcharts or graphs.

All personal information from measurement reports and questionnaires have been censored and all data displayed have been made anonymous to ensure no linking information between participants and the report [Council of European Union, 2016]

The group would like to thank Associate Professor Rasmus Lund Jensen for active discussions on indoor climate and Assistant Engineer Claus Skipper Vestergaard for help with equipment design.

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Kasper Kiis Jensen
kkje13@student.aau.dk

Mikkel Krogh Simonsen
mksi13@student.aau.dk

Part I

Report

1 | Introduction

The comfort of a dwelling can be based on four main parameters; temperature, lighting, air quality and acoustics. The first priority is having a comfortable temperature, the second is having comfortable and natural lighting, thirdly a pleasant air quality and lastly not being disturbed by noise and having good room acoustics.

In general most of these parameters are fulfilled and have been improved upon through the years with examples such a classification schemes for energy in 1996 [Energi-, Forsynings- og Klimaministeriet, 2012] and the implementation of a sound classifications in 2001 [DS-490, 2007]. Comfortable room acoustics on the other hand, have worsened. Throughout the last century the interior design have changed drastically, going from large cushioned fabric furniture, thick drapes and rugs to hard surfaces like tiles/shingles, hard wood surfaces and large panoramic glass panes. A graphical representation of this development can be seen on figure 1.1 showing three major design styles from the last century.

(a) Art Deco (circa 1920-1940) **(b)** Mid-Century Modern (circa 1940-1980) **(c)** 21st Century (circa 2000-Present)

Figure 1.1: Graphical illustration of three major design periods throughout the last century [Belman, 2015].

With building acoustics being in its early stages in the late 1800 [Sabine, 1922][Sabine, 1977] and acoustic measurements being time consuming, it was not until the late 1900 that larger acoustical surveys started being published. In 1972 a paper was published which investigated reverberation time of 50 living rooms and kitchens in England [Jackson and Leventhall, 1972][Burgess and Utley, 1985]. More recently, in 2005, approximately 11.500 buildings were measured in Spain [Díaz and Pedrero, 2005]. Neglecting the geographical differences between the buildings in Spain and England, it shows over a time period of 20 years an increase in reverberation time of 57% @ 125 Hz and 29% @ 4 kHz within rooms of the same volume.

Alongside the increase of reverberation time, advances within understanding acoustical properties and standardization of acoustical parameters for performance spaces (e.g. concert halls) [ISO 3382-1, 2009] have been made. Very few studies however have been made on correlating subjective likeness and objective parameters in dwelling's rooms [Vanwelkenhuysen, 1972].

When describing the acoustic comfort of a room it is defined by both noise and the rooms influence on sound. In this project the acoustic comfort is defined as the room acoustics and not noise, since noise is already classified and well defined in DS 490 and ANSI S12-2 [ANSI S12-2, 2008].

In DS 490 which should be a sound classification of dwellings for both noise and acoustic comfort, the only parameter describing the acoustic comfort is reverberation time as seen in table 1.1. Class A is the best and class D is the worst. It is however not classified for living spaces but only for stairwells, hallways and common rooms. Also, every class has the same or almost the same reverberation time, rendering the classes meaningless.

Room Type	**Class A** T in s	**Class B** T in s	**Class C** T in s	**Class D** T in s
In stairwells and hallways with access to more than 2 dwellings or business units at 500 Hz, 1000 Hz and 2000 Hz	1.0	1.0	1.3	1.3
In hallways at retirement homes where the areas is used somewhat for living at 500 Hz, 1000 Hz and 2000 Hz	0.9	0.9	0.9	0.9
Common rooms at 125 Hz, 250 Hz, 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz	0.6	0.6	0.6	No demands
NOTE - in common rooms the limit is 0.9 at 125 Hz				

Table 1.1: Reverberation time. Limits specified as highest values in each octave band. (Translated from Danish to English) [DS-490, 2007]

The main objective of this project is to develop a proposal for a classification system of the room acoustics in domestic rooms meaning living spaces using the parameters which are deemed most descriptive. However with the surveys available being both sparse and from different countries, new data needs to be collected in order to determine the current state of dwellings in Denmark. From this main objective the following research goals are specified as:

- Investigate the current room acoustical state and likeness of domestic rooms in dwellings in Denmark.
- Analyse which acoustical parameters are most descriptive of the likeness in domestic rooms.
- Propose a classification system for the acoustic comfort in domestic rooms.

2 | Analysis

The aim of this chapter is to describe classification, room parameters and measurement requirements. In order to propose a classification a previous work of how to create a classification will be studied. The field of room acoustics contains a wide variety of parameters which could be used. These will therefore be analysed to determine which measuring technique should be used. From this measuring technique follows measurement requirements which must be complied with. These three areas are able to provide the basis for the further work.

2.1 Current Standards and Regulations

The Danish standard for acoustic classification is the DS 490 [DS-490, 2007]. The purpose of the standard is to make it easier to specify the acoustic conditions of dwellings. The acoustic conditions classified are; airborne sound insulation, impact sound insulation, reverberation time, noise from indoor technical installations and noise from traffic.

The classification scheme is based on four classes A,B,C and D, where A is the best class and D is the worst. Class C specifies the minimum requirements given in the Danish building regulations [Trafik-, Bygge- og Boligstyrelsen, 2018].

The focus of the standard has been on noise and sound insulation and not room acoustics. This is likely due to environmental noise e.g. from neighbours being a large problem in the past and in the present [Rasmussen and Rindel, 1994][Rasmussen and Ekholm, 2015]. The consequences associated with annoyance due to environmental noise has been published in a report by the World Health Organisation (WHO) which states negative responses such as anger, depression, exhaustion, tiredness and stress [World Health Organisation, 2011]. The classification of airborne sound insulation is as seen in table 2.1

Room Type	**Class A** $R'_w + C_{50-3150}$ in dB	**Class B** $R'_w + C_{50-3150}$ in dB	**Class C** R'_w in dB	**Class D** R'_w in dB
Between a dwelling or common areas and rooms with noisy activities	68	63	60	55
Between a dwelling and rooms outside the dwelling	63	58	55	50
Between common rooms	63	58	55	50
Door between dwelling and common room	32	32	32	27
NOTE - For class A and B care should be taken to sound insulation at low frequency by adding the spectral correction, $C_{50-3150}$ to R'_w. This spectral correction is used as a protection against annoying low frequency noise.				

Table 2.1: Airborne sound insulation. Limits are denoted as the weighted lowest apparent sound reduction index R'_w or $R'_w + C_{50-3150}$. (Translated from Danish to English) [DS-490, 2007]

This classification makes logical sense as the requirements becomes more strict going from class D to A. The classification of reverberation time however does not make logical sense as all classes have the same or almost same requirements as seen on table 2.2.

Room Type	**Class A** T in s	**Class B** T in s	**Class C** T in s	**Class D** T in s
In stairwells and hallways with access to more than 2 dwellings or business units at 500 Hz, 1000 Hz and 2000 Hz	1.0	1.0	1.3	1.3
In hallways at retirement homes where the areas is used somewhat for living at 500 Hz, 1000 Hz and 2000 Hz	0.9	0.9	0.9	0.9
Common rooms at 125 Hz, 250 Hz, 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz	0.6	0.6	0.6	No demands
NOTE - in common rooms the limit is 0.9 at 125 Hz				

Table 2.2: Reverberation time. Limits specified as highest values in each octave band. (Translated from Danish to English) [DS-490, 2007]

As mentioned in the introduction the classification does not specify reverberation time in domestic rooms which is surprising. Does this mean that bad room acoustics is not as bad as annoying outside noise? or is it just because bad room acoustics is not a problem? There could be reasons for not specifying reverberation time for domestic rooms, such as the number of studies are low, or it is difficult to estimate the influence of furniture. The standard does however not note any explanation.

The building regulations [Trafik-, Bygge- og Boligstyrelsen, 2018] refers to the DS 490 reverberation time in dwellings. It however specifies maximum reverberation time requirements (furnished) for e.g. classrooms ($T \leq 0.6$ s), daycare common rooms ($T \leq 0.4$ s), one man offices ($T \leq 0.6$ s) and hospital rooms ($T \leq 0.8$ s). These values are however the maximum times and not necessarily optimal reverberation times.

The DS 490 class for reverberation time and maximum reverberation time requirements from the building regulations are all the standards and regulations given in Denmark. It should be further noted that none of the literature referenced in DS 490 concerns acoustic comfort, but only noise [Bodlund and BFR., 1984][Bodlund, 1985][Bradley, 1982][Langdon et al., 1981][Poulsen and Mortensen, 2002][Rindel, 1998][Weeber, 1986]. This note is concerning due to lack of empirical data to validate the given reverberation times.

2.2 Classification Methodology

The classification work which will be studied is the COST Action TU0901 which worked with harmonizing sound insulation for all EU countries to a single classification scheme [Rasmussen and Machimbarrena, 2014a][Rasmussen and Machimbarrena, 2014b]. The work spanned four years with cooperation and discussion between approximately 90 experts from 29 European countries and three overseas countries. It considers itself as:

> *the main tool to be an acoustic classification scheme for dwellings* [Rasmussen and Machimbarrena, 2014a]

A classification scheme is understood by the TU0901 as a set of minimum three classes and is intended to reflect different levels of acoustical comfort with noise. This definition was used to find the classifications schemes across Europe. The method used for constructing a classification scheme can be divided into three steps; determining acoustic descriptors, construct classes, method for validating the building/room under test. These three steps are described below.

Determining Acoustic Descriptors

A collection of all feasible descriptors and frequency ranges for building acoustics were gathered, meaning airborne sound insulation, impact sound insulation, façade sound insulation etc.. A discussion was then had to determine the most appropriate descriptors and assessment methods.

The emphasis was on creating practical and easy understood descriptors and frequency ranges. A single number quantity was therefore chosen instead of using a single number quantity with a spectrum adaptation term. It was preferred to use standardized level difference (D_{nT}) over apparent sound reduction index (R') as standardized level difference is standardized according to reverberation time instead of equivalent absorption area which should be easier to understand. Both 100 Hz and 50 Hz as options for the lower frequency boundary was chosen, due to 50 Hz being difficult to measure. The higher frequency boundary was chosen depending on quantity but for e.g. airborne sound insulation it was chosen to be 3150 Hz. An example of the proposal for airborne sound insulation is seen in table 2.3.

Aspect	**Quantity**	**Frequency range**	**Assessment**	**Provisional notation single number**
Airborne insulation	D_{nT}	50-3150 Hz or 100-3150 Hz	A_{pink}	$D_{nT,50}$ and $D_{nT,100}$

Table 2.3: Example of acoustic descriptor proposed by TU0901. [Rasmussen and Machimbarrena, 2014a]

Reasons which were repeated for several quantities were: good correlation with perception, long experience and data available, simple to explain, easy to use and reproducibility. On the basis of the descriptors a proposal for a classification was made.

Acoustical Classification Scheme Proposal

The classification scheme proposed, for dwellings, consist of six classes A,B,C,D,E,F. Class A being the best class and class F being the worst. A separate definition "no performance determined" can be used if no acoustic performance is required, the performance is outside the indicated classes or not determined.

The classification scheme covers classes for airborne sound insulation, impact sound pressure levels, sound pressure levels in dwellings from service equipment and maximum indoor sound levels or façade insulation. Furthermore a class for reverberation time is given however it is not mandatory. The explanation for the different types of classes A,B,C etc. are as seen in table 2.4.

Class	General	Sound insulation judged poor
A	A quiet atmosphere with a high level of protection against sound	less than 5%
B	Under normal circumstances a good protection without too much restriction to the behaviour of the occupants	around 5%
C	Protection against unbearable disturbance under normal behaviour of the occupants, bearing in mind their neighbours	around 10%
D	Regularly disturbance by noise, even in case of comparable behaviour of occupants, adjusted to neighbours	around 20%
E	Hardly any protection is offered against intruding sounds	around 35%
F	No protection is offered against intruing sounds	50% or more

NOTE: the indicated percentages are just a global indication; the trend is rather well based in litterature, but the absolute numbers depend very much on the setting and wording of questionnaires used.

Table 2.4: Description in general terms of the quality of the different classes. [Rasmussen and Machimbarrena, 2014a]

The classification scheme proposed is based on an unipolar scale which goes from non-negative to negative (sound insulation judged poor) because noise annoyance cannot be positive. If this scale is compared to this projects goals it could be difficult to implement an unipolar scale as acoustic comfort could be both positive and negative. The basis however is to construct the classes based on how high a percentage of respondents judge an objective measure to be good or bad.

Guidelines for Verification

In order to classify a room, dwelling etc. guidelines for verification should be in place. There are general guidelines such as the classification applies from a certain date, it is valid as long as the building is unaltered and the relevant standards should be applied when measuring. If a unit needs to be classified not all rooms needs to be verified. A deemed expert in acoustics should select the spaces to be measured in order to ensure a sufficient representation of the unit.

2.3 Room Acoustical Parameters

From section 2.2 the parameters which should be used to classify acoustic comfort should be practical, easy to understand, good correlation with perception, long experience and data available. Because of these criteria the parameters which were studied in this section are described in current standards. A more detailed description, also with regards to calculation, of all parameters can be found in Appendix A.

The standards which were studied were ISO3382-1 [ISO 3382-1, 2009] and IEC60268-16 [IEC 60268-16, 2011]. From these two, four main categories were defined; reverberance, sound level, clarity and intelligibility. A fifth category called spaciousness could be defined. This category was however excluded due to it not being applicable in dwellings as it is reliant on specific use cases such as sound coming from a stage into an audience. The four categories are described below.

Reverberance The perceived reverberance of a room can be described with parameters for reverberation time. The reverberation time describes how long it takes for the sound to decay 60 dB. Reverberation time is well defined within building acoustics and is generally the most used parameter in room acoustics [ISO 3382-2, 2008]. It is therefore easy to compare with previous work. Reverberation time is described using the notations EDT,T_{20},T_{30},T_{60} which ideally all tell the same but are defined based on the amount of available SNR during recording. Linked to reverberance is equivalent absorption area denoted A which specifies the relationship between volume and reverberation time. From the equivalent absorption area the absorption α of a room can be determined as well, dividing A with the absorption area of the room, resulting in a volume independent coefficient [Kuttruff, 2016].

Sound level The perceived sound level in a room can be described with the parameter sound strength denoted G. The sound strength describes how much the room naturally amplifies the sound by use of reflections. The sound strength defines the difference between the impulse response of the room and the impulse response of the loudspeaker, used during measurement, measured at 10 meters distance. The parameters has been and is mainly used for performance spaces [ISO 3382-1, 2009].

Clarity The perceived clarity of a room can be described by clarity measures. Clarity measures compare the difference between the energy in early reflections and the energy in late reflections. The clarity measures can be described with the parameters clarity (C), definition (D) or centre time (Ts). Depending on the purpose of a room the limit to what is early and late reflections is set to either 50 ms for speech or 80 ms for music. Clarity measures are mainly used for performance spaces [ISO 3382-1, 2009].

Intelligibility By modelling the room like a transmission channel for speech it is possible to determine the SNR using a modulation transfer function (MTF) [Schroeder, 1981]. From the MTF the speech transmission index (STI) can be derived which is a parameter for speech intelligibility. There are different versions of STI based on the use case [IEC 60268-16, 2011]. The STI can be measured using speech signals or can be derived from an impulse response.

Table 2.5 shows all the relevant parameters just mentioned for describing a rooms acoustical environment. The table states, when possible, the just noticeable difference along with the typical values [Hak et al., 2012]. The typical values can be misleading as they are defined for performance spaces and not domestic rooms.

Subjective listener aspect	**Acoustic quantity**	**Just noticeable difference (JND)**	**Typical range**
Reverberance	Early decay time (EDT)	Rel. 5%	1.0 s ; 3.0 s
	Reverberation time (T_{20},T_{30},T_{60})	Rel. 5%	0.3 s ; 0.6 s
	Equivalent absorption area (A)	Not stated	Not stated
	Absorption (α)	Not stated	Not Stated
Sound level	Sound strength (G)	1 dB	-2 dB; +10 dB
Clarity	Clarity (C_{50})(C_{80})	1 dB	-5 dB; +5 dB
	Definition (D_{50})	0.05	0.3 ; 0.7
	Centre time (T_s)	10 ms	60 ms; 260 ms
Intelligibility	Speech Transmission Index (STI)	Not stated	>0.36 ; 0.76<

Table 2.5: Table of room parameters. All parameters are explained in detail in appendix A

The parameters chosen for further investigation are all listed in table 2.5. The STI chosen is the full STI calculated using the indirect method, elaborated in section A.2.

At this point it clearly shows that the desired measure to obtain for analysis is the room impulse. Given that few studies have been done within acquiring large databases of room impulses and even fewer have allowed access to these databases it stands clear that a database must be obtained. The database must be obtained measuring domestic rooms to ensure realistic data. In addition to the measurements subjective opinions must gathered in order to determine how respondents perceive acoustical comfort.

To acquire a large and diverse sample size of different rooms an efficient measurement campaign is required, starting with the selection of a measurement system able to measure and calculate the impulse response of a room.

3 | Measurement Platform

With a requirement for a database of room impulses established in section 2.3 alongside the requirement that they are to be obtained by measuring domestic rooms, a data acquisition system must be selected. Since different dwellings, in potentially multi-story housing, are to be measured, a main focus should be that it is movable, lightweight and easy to set up at multiple locations. The measurements must be done with a reasonable speed not annoying occupants more than necessary. They have to be verified on-site as the option of returning to the dwelling if something is wrong in post processing is not a viable option.

To measure the impulse response in domestic rooms consistently the ISO 3382-2, is followed. This will ensure impulse responses with a high SNR and comparable reverberation times to previous studies. The ISO 3382-2 specifies both degrees of precision, procedure and needed documentation. With a demand for high quality measurement in future analysis the degree of precision must the highest; A precision method measurement. It is assumed that with a precision method measurement the most time consuming part will become the actual set-up and documentation compared to measuring and calculating.

3.1 Selection of Platform

From Aalborg University a selection of measurement platforms are available. The systems available can be divided into the following categories:

- All-in-one analyzers
  - Brüel & Kjær Type 2270 [Kjær, 2016]
  - 01dB 4-channel Harmonie Analyzer [01dB, 2002]
- USB sound cards with license based measurement software
  - Room EQ Wizard [Mulcahy, 2016]
  - Easera Pro [AFMG, 2016].
- USB sound cards using scripting languages
  - Matlab
  - Python

Both advantages and drawbacks are present in all solutions and to determine which is most suitable for the project they will be sorted against a set of desired features which allows for efficient measuring.

Support for multichannel measurement set-up. The primary design goal is to decrease the overall time used on measurements. It is known from ISO 3382-2 that at least 12 combinations of microphone and source positions are required with a minimum of three microphone and two source positions. Prior to measuring it is not known what the optimal combination of equipment will be, the system must hence be able to handle different numbers of microphones and sources. This allows for a flexible adjustment of the system during development to optimize the measurement flow. The Room EQ Wizard fails to comply with this feature as there is only 1 channel in Room EQ wizard.

Support for on-site calibration. The system is to be used in none controlled environments i.e. not acoustic laboratories. If a calibration is required on-site, a robust calibration procedure is required. In case of a high noise floor or distinct tonal noises being present on-site it can potentially impact the calibration of the microphones. The remaining systems all have this feature available.

Support for on-site analysis. All measurements needs to be correctly recorded and validated. An on-site analysis tool is therefore required. The system needs to allow for visualization of data in time, frequency and fractional octave bands for validation. As reverberation time is the most requiring parameter to extract from the impulse it is essential that at least the T_{20} value for all fractional octave bands can be calculated and evaluated during measurements to ensure high enough SNR. This feature is to some extended also available in all remaining solutions.

Export options of measurement data to third-party analysis program. The system must be able to export all measurement data, not limited to single number values or post processed data only, to a format which a known scripting language or analysis software can handle for in-depth analysis. Both analyzers fail to comply with this requirement. The Brüel and Kjær Type 2270 Analyzer only allows for single number values to be exported, where 01dB is only slightly better and allows for export to a proprietary XML format.

Support for automatic documentation. To comply with ISO 3382-2 it is required to document the entire procedure. The documentation allows for reconstruction of the set-up or explanation of abnormalities in the measurement at that specific location. To ensure all ISO 3382-2 parameters are documented it should be possible to add all needed parameters into the program. The automatic documentation is a very important parameter for making efficient measurements as a manual documentation procedure will increase the time for each measurement. Only 01dB allowed for a simple one page documentation.

Protocol supported measurement procedure. To ensure all requirements from ISO 3382-2 with regards to room dimensions, temperature, humidity and microphone/source-positions are uphold, a protocol driven measurement system is desired. The system is to calculate the needed requirements for positioning based on basic essential information like room dimensions. Furthermore it must be able create the correct stimuli and design proper filters required by ISO 3382-2. None of the remaining systems allows for any protocol supported measurement.

By rules of elimination the most suitable measurement system is chosen to be a custom graphical user interface utilizing the scripting language Python. The all-in-one analyzers does not provide sufficient flexibility in regards to documentation, exportability and aid with the measurement procedure. The software solutions also fails in providing aid with the measurement procedure. With the most time consuming part of an ISO 3382-2 measurement being the actual set-up and documentation compared to the measuring the current available software platform can not be used. Bearing in mind the development time will increase, reducing the actual time available for measuring. By creating a GUI it is possible to fulfil all the needed requirements as stated above allowing for very efficient measurements.

3.2 Requirements

By selecting a sound card controlled by custom GUI it is vital that all standard regulations and requirements are fulfilled, complying with current rule sets for acoustic measurements in buildings set forth by the governments building research institute (Statens Byggeforskningsinstitut) [Rasmussen, 2017]. Their requirements state a certain amount of accuracy from the equipment alongside a calibration of the system with equal amount of precision. Furthermore it is stated to have a certain degree of documentation with traceability on all equipment.

1. **Use equipment complying with at least IEC 61672-1 class 1 specifications seen in table 3.1 [IEC 61672-1, 2014]**.

Frequency [kHz]	0.25 to 1	>1 to 2	>2 to 4	>4 to 8	>8 to 12.5
Tolerances [dB]	1.0	1.0	1.5	2.5	4.0

Table 3.1: IEC 61672-1 class 1 magnitude tolerance requirements. [IEC 61672-1, 2014]

2. **The equipment must be calibrated using IEC 60942 class 1 calibrators, calibrating with a tolerance of ± 0.3 dB [IEC 60942, 2017]**.
3. **The equipment and calibration values must be documented with calibration dates, internal and serial reference number.**

The room impulse response calculation method must comply with ISO 18233, which states that achieving an impulse using an impulsive source, like a clapboard or signal gun, is in general a bad idea since the spectral content of the impulse cannot be controlled and is hence not repetitive.

Playing a certain stimuli, like a swept sine, allows for a controlled spectral content and the impulse can be calculated using linear deconvolution or spectral division.

4. **The impulse must be calculated using linear deconvolution.**

The spectral content of the sweep must cover the all fractional bands desired. A pink sweep is desirable to obtain a decent low frequency resolution [ISO 18233, 2006].

5. **The stimuli must cover all fractional-octave bands of interest, having a pink spectrum in each bands entire 3 dB bandwidth.**

It is allowed to vary the spectral content in the sweep by changing the sweep rate, but the envelope must remain constant. Having a constant envelope ensures the same signal headroom throughout the measurement. No tolerances were stated for the requirement and they are chosen to be within the same tolerances as the chosen equipment tolerance.

6. **The stimuli must have constant envelope within the desired frequency range with the tolerance of the chosen sound card.**

To ensure the room impulse is obtained with the highest accuracy and repeatability it must done in accordance with the ISO 3382-2 precision method. A precision method measurement requires an omni-directional source and specifies a minimum frequency range for the transducers. The ISO 3382-2 also states both distances for reflective surfaces, sources and microphones along with the amount of source and microphone combinations. The standard is furthermore a requirement from BR15.

7. **Have an omni-directional source with a directivity with a maximum deviation as stated in table 3.2 and a frequency response of 100-5000 Hz [ISO 3382-1, 2009]**

Frequency [Hz]	125	250	500	1000	2000	4000
Maximum deviation [dB]	± 1	± 1	± 1	± 3	± 5	± 6

Table 3.2: Maximum deviation of directivity of source in decibels for excitation with octave bands of pink noise and measured in free field [ISO 3382-1, 2009].

Since it is desired to calculate the reverberation time from the impulse it is crucial that the Impulse-To-Noise ratio (INR) is high enough [Hak et al., 2012]. For evaluating a T_{20} value a dynamic range of 35 dB is required and with DS 490 allowing for a maximum noise level of 38 dB(A) traffic noise a potential need for playing in excess of 90 dB(A) is required. Furthermore, the ISO 3382-2, states how to evaluate the decay curves for each frequency band, specifying how to perform linear regression on the decay curve.

8. **The source must be capable of producing sound pressure levels at or above 90 dB(A).**

Special requirement for the fractional octave band filters are also noted in ISO 3382-2, demanding a certain amount of attenuation in the stop bands. The demands for the filters are specified in IEC 61260-1 as class 1 [IEC 61260-1, 2014].

9. **All fractional octave filters used for evaluation of decay curves must be IEC 61260 class 1 compliant.**

When performing an ISO 3382-2 measurement it is required to document the entire procedure. The documentation required concerns documentation of the environment, calculation procedures, results, placements etc. The entire list of documentation requirements are all stated in ISO 3382-2.

10. **Conform with the documentation required in ISO 3382-2.**

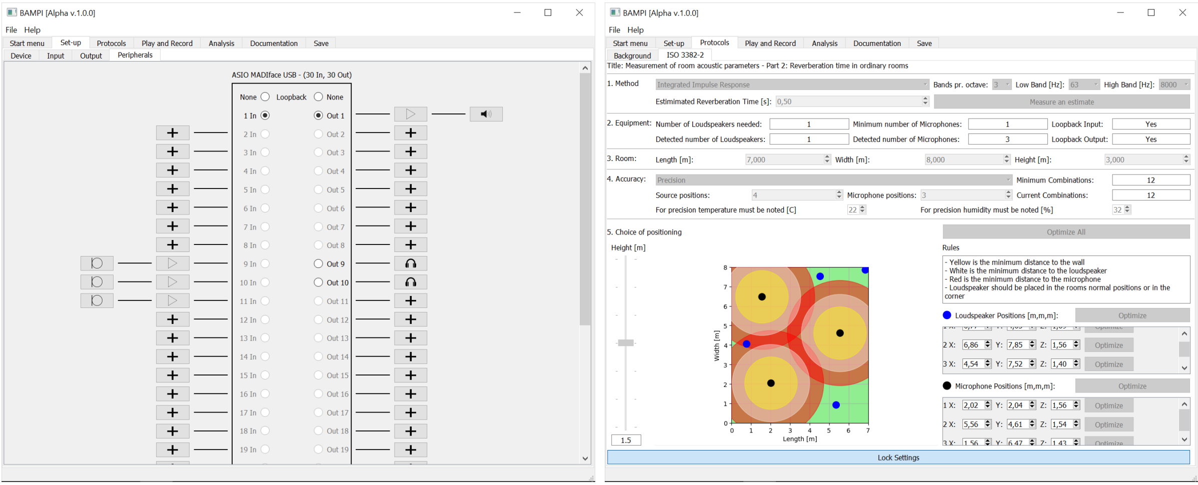
With all requirement stated it is now possible to develop a measurement program complying with the requirements.

3.3 Measurement Program

The program is developed in Python 3.6 using PyQT5 bindings [Riverbank Computing, 2018]. The program will further on be denoted as Building Acoustic Measurement Program Interface (BAMPI). An in depth description of each menu can be found in appendix B.

The BAMPI program handles the low level communication with all driver compatible USB sound cards. The user is provided with the option to chose between different driver communication protocols e.g. ASIO [Steinberg, 2017] or WASAPI [Windows, 2018]. When the sound card is selected it will automatically adjust the program to the amount of channels available and allow the user to select the desired channels, apply filters and calibrate the channels. After calibration it is possible to add additional hardware to the sound card like pre-amplifiers, power amplifiers, loudspeakers or microphones as seen on figure 3.1a. The additional equipment can also be calibrated, ensuring the gains throughout the entire measurement chain is known. In case of the set-up being used multiple times it is possible to save the entire set-up, saving sound card and equipment settings including calibrations dates.

To assist in documenting all ISO 3382-2 requirements and help with placement of equipment, a protocol tab is available as seen on figure 3.1b. A complete user guide for an ISO 3382-2 measurement can be seen appendix C. By providing BAMPI with room geometry, a graphical overview of viable placements will be shown, alternatively a genetic algorithm [Kramer, 2017] can be used to provide a suggestion by maximizing the distance between all equipment.

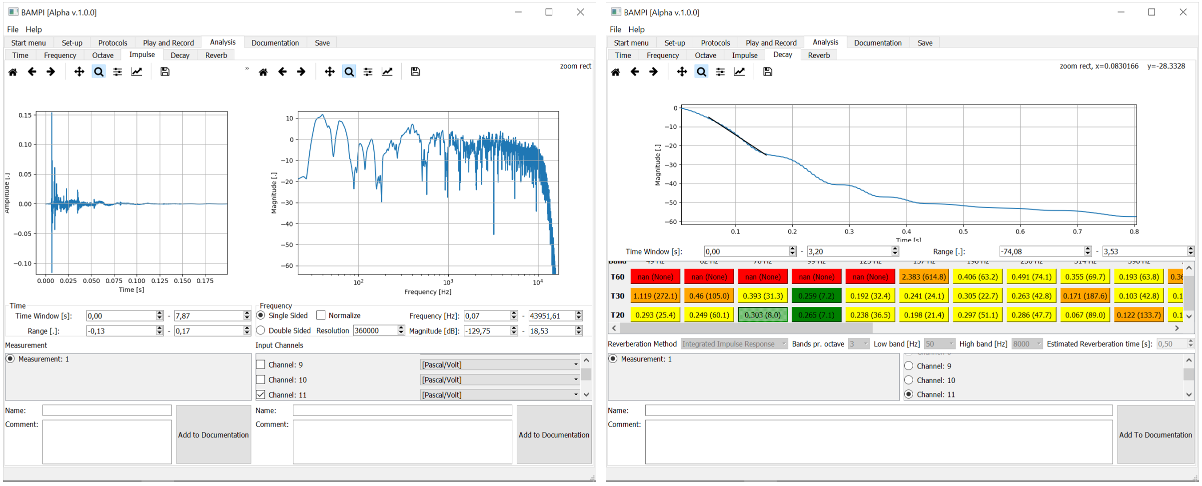


(a) Device configuration. **(b)** ISO 3382-2 protocol.

Figure 3.1: Set-up interface.

When all information about equipment, positions and the environment has been noted it is possible to lock the protocol. Locking the protocol allows for BAMPI to create all essential filters, stimuli and procedure for the user to follow. This allows for correct and identical measurement settings each time.

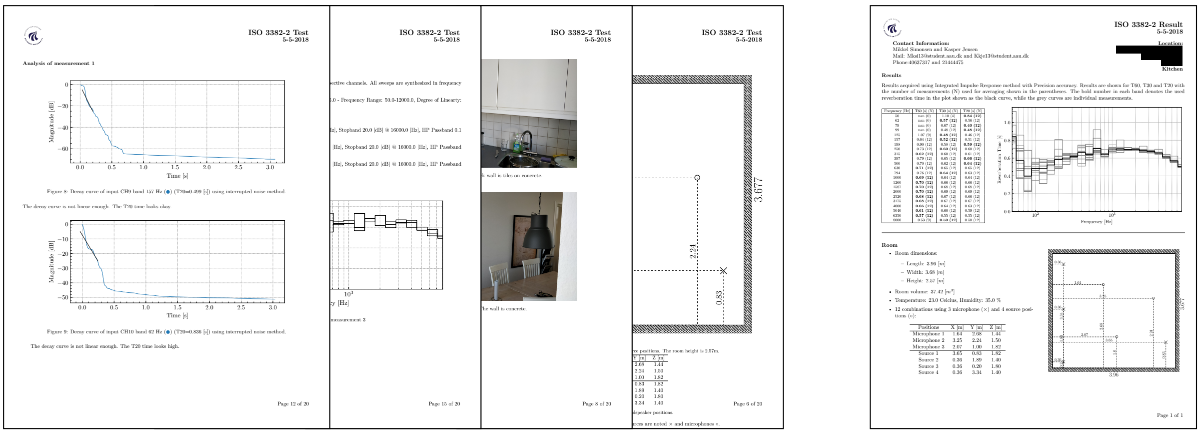
An analysis and evaluation tool has been created for when measurements have been performed. As the main objective is to measure room impulses a visualization tool for the room impulse response is available as seen on figure 3.2a. Alternatively it is possible to both see and listen to the recorded signal in time. The recorded signal can also be visualized using an n-point FFT or fractional octave bands. An evaluation tool for decay curves are also available as seen on figure 3.2b to determine if the measurement have produced usable reverberation times. The tool calculates all frequency bands selected for measurement and provides a linear fit with the deviation of linearity in per mil. This ensures the majority of the measured room impulses are suitable for further analysis.



(a) Analysis of impulse. **(b)** Evaluation of decay curves.

Figure 3.2: Analysis and evaluation tools available in BAMPI.

When all the measurements have been made and the reverberation times have been checked a semi-automatic documentation process is provided for saving both recordings and settings. The BAMPI program allows the user to input photographs of the surroundings, additional equipment and alternative procedures into a documentation environment. BAMPI will save all automatically generated settings and user inputs into one folder. The folder is formatted identically each time, ensuring potential analysis software have the same information available for each measurement. Besides all raw data, a full bodied report and single-page result .pdf is created. A full bodied report is illustrated on figure 3.3a and can be seen in full in appendix D. A result page is illustrated on figure 3.3b and can be seen in appendix E.



(a) Full documented measurement report. **(b)** Single page result.

Figure 3.3: BAMPI delivers both a full-bodied report alongside a single paged result overview.

3.4 Acceptance Test

The developed system is tested against the requirements noted in section 3.2 where the results for each requirement can be seen in table 3.3 below. For the entire documented acceptance test refer to appendix F.

Req no.	Requirement	Reference (Section)	Result
1	Use equipment complying with at least IEC 61672-1 class 1 specifications seen in table 3.1	F.1.1	✓
2	The system must be calibrated using IEC 60942 class 1 calibrators, calibrating with a tolerance of ± 0.3 dB	F.1.2	✓
3	The equipment and calibration values must be documented with calibration dates, internal and serial reference number.	F.1.3	✓
4	The impulse must be calculated using linear deconvolution.	F.1.4	✓
5	The stimuli must cover all fractional-octave bands of interest, having a pink spectrum in each bands entire 3 dB bandwidth.	F.1.5	✓
6	The stimuli must have constant envelope within the range with the tolerance of the chosen sound card.	F.1.6	✓
7	Have an omni-directional source with a directivity with a maximum deviation as stated in table 3.2 and a frequency response of 100-5000 Hz	F.1.7	✓
8	Produce sound pressure levels at or above 90 dB(A).	F.1.8	✓
9	All fractional octave filter used for evaluation of decay curves must be IEC 61260 class 1 compliant.	F.1.9	✓
10	Conform with the documentation required in ISO 3382-2.	F.1.10	(✓)

Table 3.3: Acceptance test.

All requirements are accepted and the system is deemed applicable for the measurement campaign. To support the acceptance test further, an electrical validation is documented in appendix G. The electrical validation ensures the system and sound card measures voltages correctly and is suitable for data acquisition. Furthermore, an acoustical validation is documented in appendix H. The acoustic validation is used to compare with known measurement systems widely used and validates that calculation methods are satisfactory.

4 | Questionnaire

The subjective data will be gathered using a questionnaire. A questionnaire was chosen due to it being scalable if a large quantity of dwellings were to be measured providing quantitative data on which statistical methods can be applied. This chapter documents the designed questionnaire and an in-depth documentation of the development can be found in appendix I.

The questionnaire is designed to ask about the acoustic environment of the living room, kitchen and bedroom which were deemed the three most common rooms. It is assumed that people would answer differently if asked to evaluate each room individually instead of one large single evaluation of the dwelling, as the acoustics in a kitchen and living room can be very different. In addition evaluating three rooms per dwelling will give three times the samples. The questionnaire furthermore asks the respondents to rate an overall noise annoyance, acoustic satisfaction and finally rate how sensitive they are to sound.

The creation of the questionnaire is inspired by previous work done by COST TU0901 within sound insulation [Rasmussen and Machimbarrena, 2014a], REBUS [Knudsen et al., 2017] and ISO 15666 [ISO 15666, 2003] covering assessment of noise annoyance by means of social and socio-acoustic surveys.

Each question starts with a sentence inspired from ISO 15666, which defines a sentence commonly used in surveys. This is followed by the question designed for this questionnaire. Preceding the question is an explanation of the designed scale ending with a recap of the question to improve understanding.

Sound and Comfort

It was chosen to use Semantic Differential (SD) scales which measures a respondents reactions to words. SD scales are a proven way of measuring respondents reactions and it is simple to understand. [Summers, 1970]. Ideally the words used in SD scales should be developed using a proper word elicitation [Al-Hindawe, 1996]. However because of time constraints this is not possible. The words found are therefore a product of an internal word elicitation and discussions with the projects supervisor, refer to Appendix J. The questions and scales for sound and comfort can be seen below and on the next page.

Thinking about the last 12 months or so, when you are here at home. Which word does best describe the living rooms influence on sound?
The scales describes opposites. For example if the living room influences sound such that it feels more dead than resounding then you should mark 3 for extremely dead, 2 for quite dead, 1 for slightly dead. Mark 0 if it is neither. Please answer the questions with your immediate reaction.
The living room influences sound so it feels?

	3	2	1	0	1	2	3	
Dead	☐	☐	☐	☐	☐	☐	☐	Resounding
Unclear	☐	☐	☐	☐	☐	☐	☐	Clear
Compact	☐	☐	☐	☐	☐	☐	☐	Spacious
Quiet	☐	☐	☐	☐	☐	☐	☐	Noisy
Uncomfortable	☐	☐	☐	☐	☐	☐	☐	Comfortable
Attenuated	☐	☐	☐	☐	☐	☐	☐	Amplified
Remote	☐	☐	☐	☐	☐	☐	☐	Enveloping
Soft	☐	☐	☐	☐	☐	☐	☐	Hard
Uneasy	☐	☐	☐	☐	☐	☐	☐	Calm
Absent	☐	☐	☐	☐	☐	☐	☐	Present

Table 4.1: sound segment scales.

Thinking about the last 12 months or so, when you are here at home. Which word does best describe the feeling you have when you are in the bedroom?
The scales describes opposites. For example if you feel more sleepy than awake then you should mark 3 for extremely sleepy, 2 for quite sleepy, 1 for slightly sleepy. Mark 0 if it is neither. Please answer the questions with your immediate reaction. **When I am in the bedroom I feel?**

	3	2	1	0	1	2	3	
Sleepy	☐	☐	☐	☐	☐	☐	☐	Awake
Enclosed	☐	☐	☐	☐	☐	☐	☐	Open
Uncomfortable	☐	☐	☐	☐	☐	☐	☐	Comfortable
Disinterested	☐	☐	☐	☐	☐	☐	☐	Committed
Small	☐	☐	☐	☐	☐	☐	☐	Large
Sad	☐	☐	☐	☐	☐	☐	☐	Happy
Dull	☐	☐	☐	☐	☐	☐	☐	Energetic
Pessimistic	☐	☐	☐	☐	☐	☐	☐	Optimistic
Inattentive	☐	☐	☐	☐	☐	☐	☐	Attentive
Uneasy	☐	☐	☐	☐	☐	☐	☐	Calm
Dispirited	☐	☐	☐	☐	☐	☐	☐	Lively
Stressed	☐	☐	☐	☐	☐	☐	☐	Relaxed

Table 4.2: Comfort segment scales.

Noise

The purpose of noise annoyance is to acquire the dwellings impact on noise. As it is impossible for people sitting in the living room to disregard noise coming from the e.g. the kitchen. It is chosen to ask about specific noise sources in the dwelling instead of asking about noise in the living room, kitchen and bedroom separately. The different noise sources stated should be able to cover most kind of normal noise sources which could be present.

The scale now shifts to the scale designed in section I.2, which is a numerical 11-point scale based on ISO 15666. The advantage of the numerical 11-point scale is that it is a base-10 numeric system which most people are familiar with. Beside the scale a "Don't know" possibility is added, as it is important to have answers for every possibility [Walonick, 2003]. If the respondent has a noise source which is not specified the respondent can add it to the list and rate it on the same scale as the specified ones. The question asked and the scale can be seen below.

Thinking about the last 12 months or so, when you are here at home how much does **noise from inside your dwelling bother, disturb or annoy you?**
The scales go from 0 to 10 where 0 is not at all and 10 is extremely.

	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Don't know**
Unwanted speech	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Furniture being dragged across the floor	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Clinging porcelain or ceramics	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Slamming doors	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Electric appliances (TV, loudspeakers, consoles)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Appliances (freezer, refrigerator)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Kitchen tools (blender, food processor)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Technical installations (exhaust hood, air condition)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Other noise: ____________________	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Table 4.3: Noise segment scales.

Satisfaction

The purpose of the satisfaction segment, is to have a direct satisfaction rating of all three rooms. This will make it possible to figure out which sound and comfort scales have a large influence on the satisfaction. The question and scales can be seen below.

Thinking about the last 12 months or so, when you are here at home **how satisfied are you with the rooms influence on sound** in the following rooms?
The scales describe satisfaction from 0 to 10 where 0 is extremely unsatisfied, 5 is neither and 10 is extremely satisfied.

	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Don't know**
Living room	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Kitchen	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Bedroom	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Table 4.4: Satisfaction segment scales.

Sensitivity

The last segment of the questionnaire is a measure of how sensitive the respondent is. This could help to compare respondents with each other. The sensitivity is measured by asking the respondent to rate their annoyance in different scenarios instead of asking the respondent directly for their sensitivity as this question could be difficult to answer. The question and scales can be seen below.

How much would **you feel bothered, disturbed or annoyed in the following scenario?**
The scales go from 0 to 10 where 0 is not at all and 10 is extremely.

	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Don't know**
When you are in a resounding room	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
When the TV or radio is turned up	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
When the neighbour is having a party	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
When a lot of people talk at the same time	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Table 4.5: Sensitivity segment scales.

A complete questionnaire can be found in appendix K for English and appendix L for Danish. With a developed questionnaire, it is possible to start the measurement campaign. What follows in the proceeding chapters are an analysis of the collected data.

5 | Data Analysis

The measurement software and questionnaire were used to investigate the acoustic environment in 15 furnished dwellings in or close to Aalborg, Denmark. The purpose of this chapter is to describe the main points from the in-depth analysis found in Appendix M. This appendix presents all the different parameters mentioned in section 2.3, answers to the questionnaire scales in chapter 4 and explain in more detail the tools used for analysis such as Exploratory Factor Analysis (EFA). In the 15 dwellings the three rooms: living room, kitchen and bedroom were measured totalling 45 rooms. One bedroom was however discarded because of a human error. In addition to the measurements one resident from every dwelling answered the questionnaire. The chapter is divided into an analysis for the measurements and an analysis for the questionnaire.

5.1 Measurement Analysis

The goal of the measurement analysis is to investigate the acoustic condition of the furnished dwellings and explore if and how the 10 objective room parameters correlate. The measurements are valid in the bands from 63 Hz - 8000 Hz meaning the 50 Hz band is discarded because the required INR for T_{20} times could not be obtained in several dwellings.

The distribution of reverberation times (RT) measured can be seen on figure 5.1. The reverberation times seems to be inside the times expected for furnished dwellings. However based on literature for performance spaces the frequency characteristics of the reverberation time should in general be flat [Maekawa and Lord, 2004]. This is however not the case for the dwellings measured where the mean varies between 0.35 s and 0.5 s. which is a variation of 30 %.

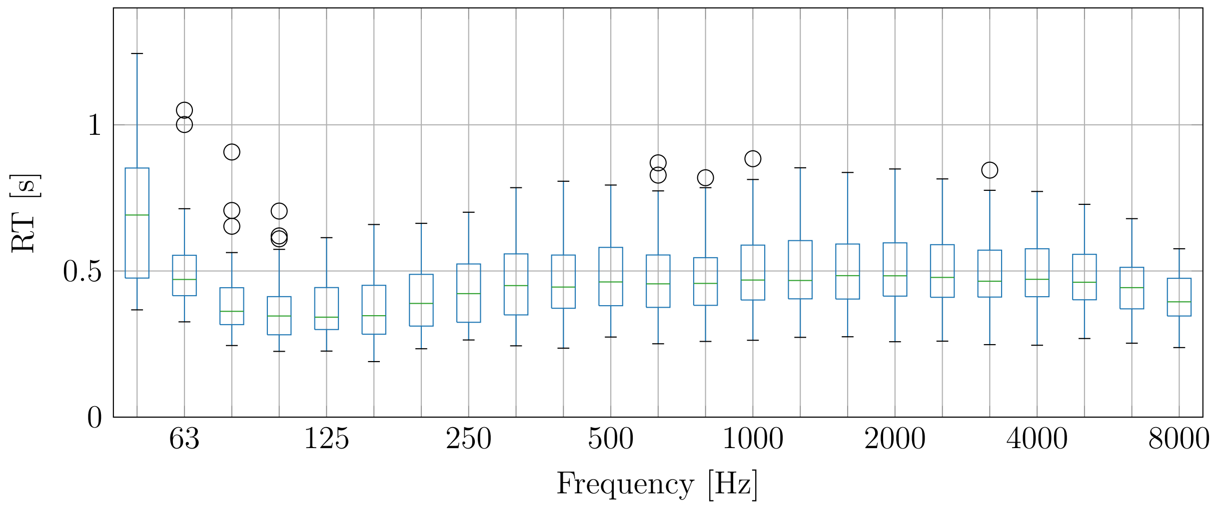
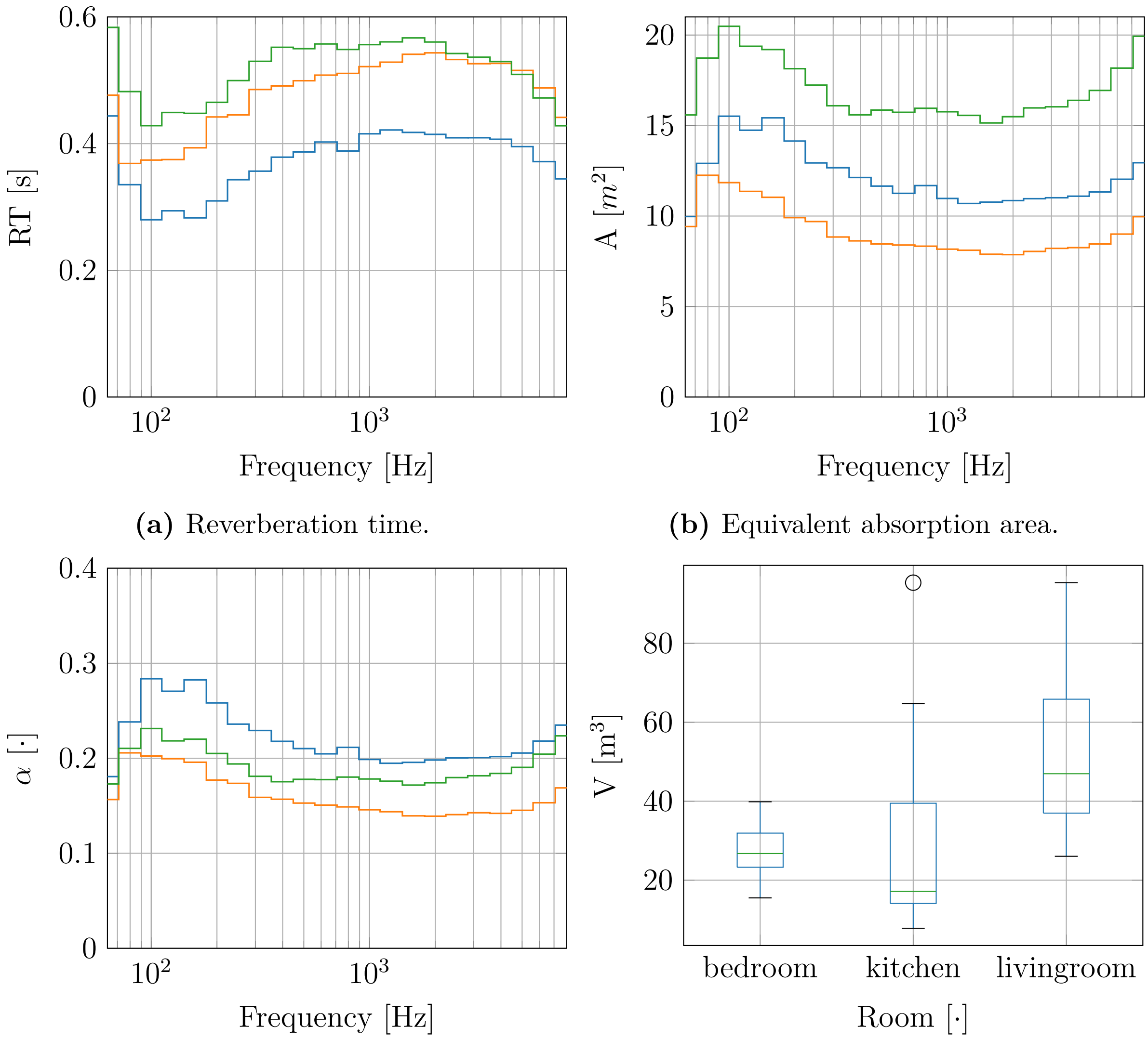


Figure 5.1: Box plot of reverberation times for the entire dataset. Two outliers in the 50 Hz band (RT=2.676 s & RT= 2.686 s) are not visible.

If the reverberation time, equivalent absorption area, average absorption and volume are compared for each room as seen on figure 5.2 some interesting tendencies can be derived. All room types have a reverberation time in the frequency bands between 100 Hz - 200 Hz which can be explained by membrane absorbers such as windows [Kinsler et al., 1999] which are present in all rooms. This is one of the large differences between performance spaces and dwellings which explains the non-flatness of the frequency characteristics.



(a) Reverberation time.

(b) Equivalent absorption area.

(c) Average absorption.

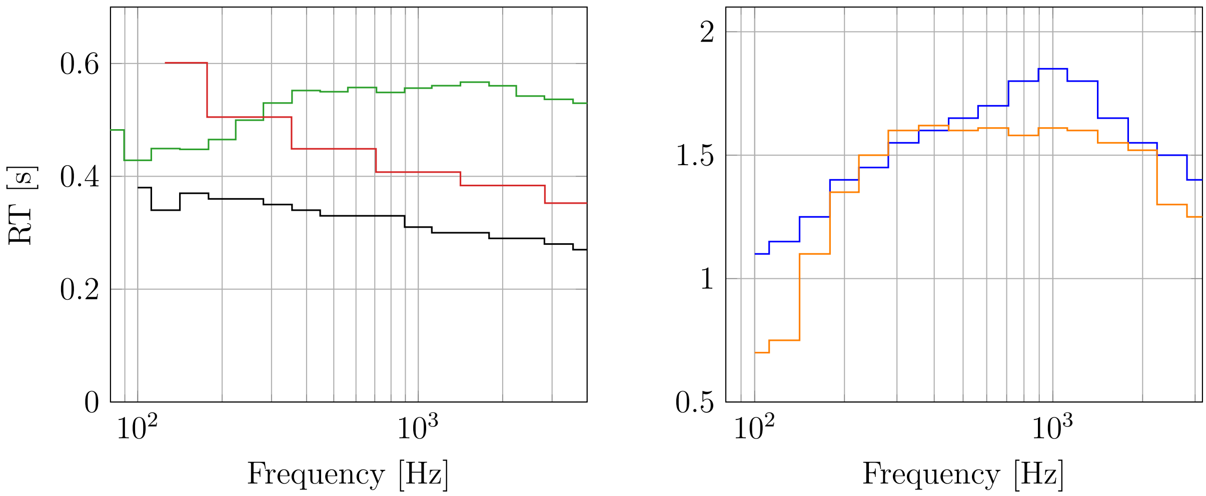
(d) Volume.

Figure 5.2: Reverberance parameters and volume of bedroom (●), kitchen (●), living room (●).

The reverberation time is highest in living rooms in the majority of bands. The kitchen however has the highest time in the highest bands which is probably due to a lack of porous absorbers. The volume of living rooms are around 40-50 % higher than the other two room types which explains the relative high reverberation time. Because of the much larger volume the equivalent absorption area of living rooms are much higher than the kitchen. The bedroom has the largest average absorption of the three types which is to be expected because of the bed which is a very large absorber.

It is known that there are errors in the volume estimation as the estimations were based on rectangular rooms which were not always the case. The equivalent absorption area and average absorption could therefore be affected by this error. The total absorption area of the room could also only be calculated from the wall, floor and ceiling area meaning the furniture is included in the calculated absorption.

If the average reverberation time for the living room is compared to previous surveys, as seen on figure 5.3a, from Britain [Burgess and Utley, 1985] and Spain [Díaz and Pedrero, 2005]. It is clearly seen that the reverberation time has changed dramatically. Because only 15 living rooms were measured in this project the reverberation times from the other surveys have been averaged to give approximately the same volume. The low number of measurements also means that the average could change in the future when more dwellings are measured.



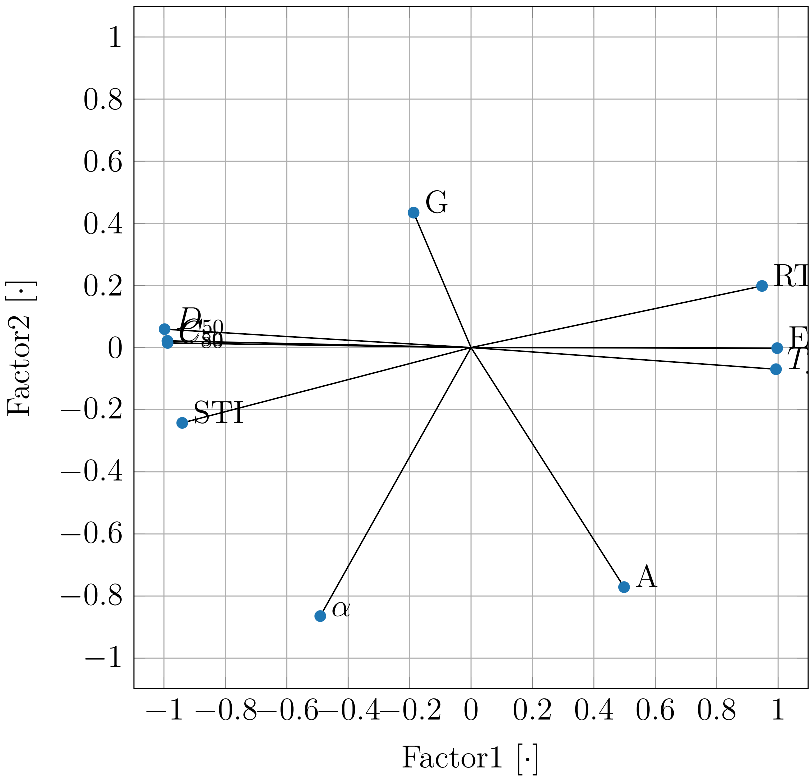
(a) Different studies of reverberation time, the mean volume for the study is noted after the @. [Burgess and Utley, 1985] @ 39 m^3 (●), [Díaz and Pedrero, 2005] @ 49.7 m^3 (●) and this project @ 49.9 m^3. (●)

(b) Reverberation times in "modern" unfurnished dwellings [Burgess and Utley, 1985]. Masonry construction (●) and Timber-frame construction (●).

Figure 5.3: History comparison with furnished and unfurnished living rooms.

When analysing the difference between the reverberation times it is noted that the frequency characteristics of the reverberation times for this project does not decrease linearly with frequency as the older surveys. The reason for this could be found in the change in interior design. The average reverberation time of unfurnished rooms measured by the British Research Establishment in 1970s can be seen on figure 5.3b. The reverberation time of these has a shape which is more equivalent to those measured in this project indicating that the interior design in Danish living rooms does not absorb as much as the interior in Britain and Spain at the time.

Because the number of dimension are 10 it is desired to explore how the dimensions correlate and reduce the dataset. An EFA is therefore used [DeCoster, 1998]. Two factors can explain 88 % of the variance in the dataset. The loading of each parameter can be seen on figure 5.4.



(a) Loadings plot.

	Factor 1 (72.37%)	Factor 2 (16.38%)
RT	**0.95**	0.20
A	**0.50**	**-0.77**
α	-0.49	**-0.86**
EDT	**1.00**	-0.00
C50	**-0.99**	0.02
C80	**-0.99**	0.01
D50	**-1.00**	0.06
Ts	**0.99**	-0.07
G	-0.19	0.43
STI	**-0.94**	-0.24

(b) Loadings Matrix.

Figure 5.4: Loadings from EFA.

From the loadings plot it can be seen that **factor 1** is based on RT, EDT, T_s, STI, C_{50}, C_{80} and D_{50} meaning that these are all highly correlated. This was not expected because in large performance spaces clarity measures and reverberation time are not as highly correlated [Pelorson et al., 1992]. Furthermore in performance spaces strength is highly correlated with the clarity measures which is not the case either. Factor 1 is interpreted as the reverberance of the room. A low reverberation time thereby equals a high clarity and vice versa. **Factor 2** is based on A and α. This is interpreted more as the absorption of the room. A high absorption of the room equals a low strength and vice versa.

On figure 5.5 the scores based on the loadings are seen with four samples highlighted using a picture of the interior design. It can be seen that the bedroom in the lower left corner is a small room (26 m^3) with a low reverberation time (0.267 s). The living room in the lower right corner is a living room (68 m^3) with a low reverberation time (0.422 s) because of the interior design which is heavy furniture and rug on rugs. In comparison the small kitchen in the upper left corner (16 m^3) has almost the same reverberation time (0.454 s) as the living room. The other living room seen in the upper right corner is a combined living room and kitchen (95 m^3) with a reverberation time which is relative low (0.7 s) based on the large volume which is why it is placed lower on factor 2.

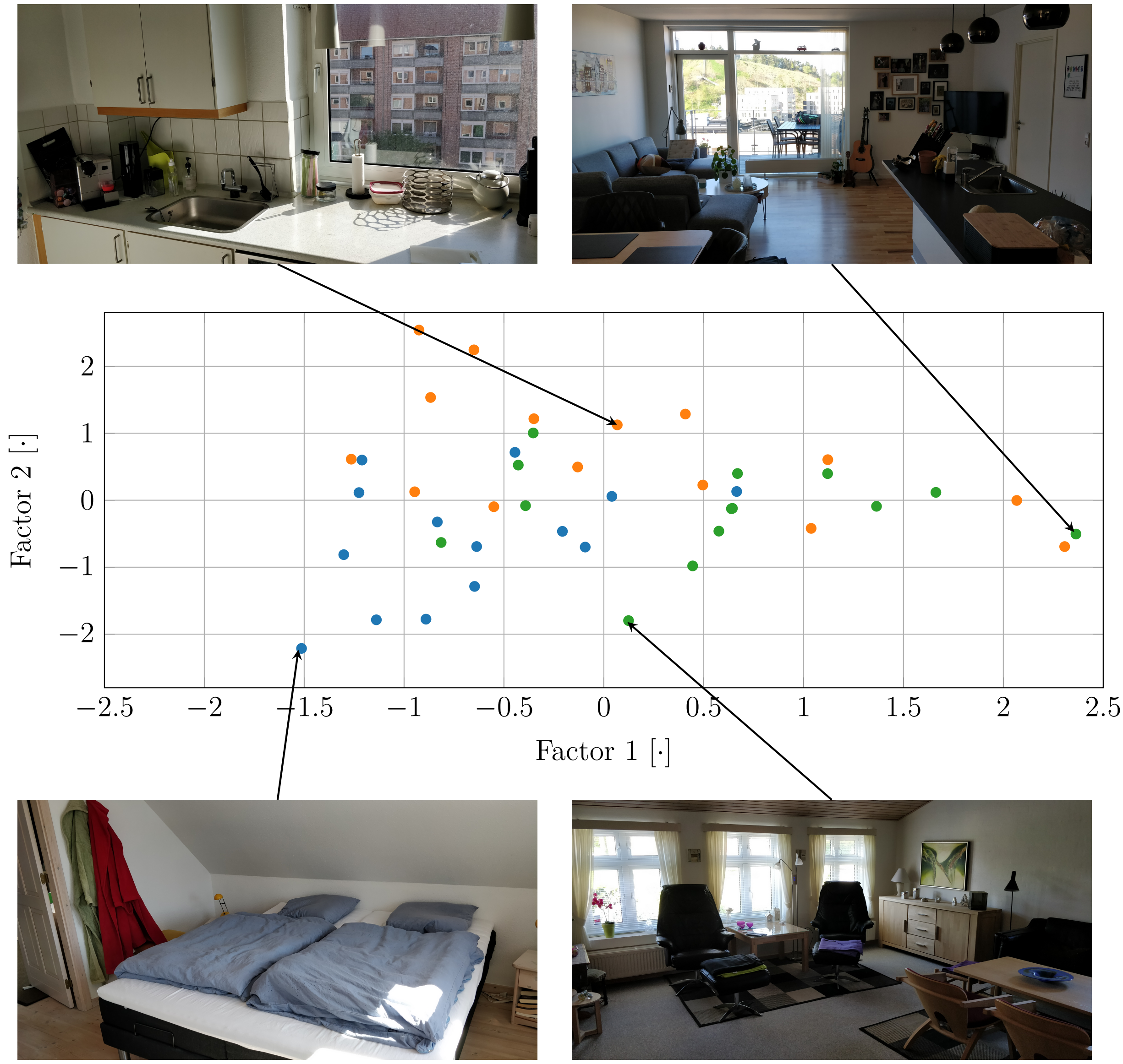


Figure 5.5: Score plot with highlighted samples. The rooms are bedroom (●), kitchen (●), living room (●).

5.2 Questionnaire Analysis

The goal of the questionnaire analysis is to find the factors behind the subjective answers and investigate what the likeness of the dwellings are in general. Each questionnaire contains 82 answers based on 38 different scales. Because the sound, comfort and satisfaction segments are answered for three rooms the number of answers are 45 instead of 15. The noise and sensitivity segments are only answered 15 times meaning no clear distribution can be seen. The two segments are for this reason discarded from further analysis. The population of respondents range from 23 - 54 years old and no respondent reported any known hearing disorders.

The answers to the sound segments seems to be normal distributed on all scales. The mean answers to the sound segment for each room can be seen on figure 5.6. From the answers it can be seen that there is a clear distinction between the rooms on the majority of the scales and the different room types have different attributes. Some things to note is that the rank of room types for the scales dead/resounding matches the average absorption parameter and not reverberation. The bedroom is almost rated as spacious as the living room even though the volume of the bedroom is much smaller than the living room. The living room is rated the most amplified but it is neither most resound.

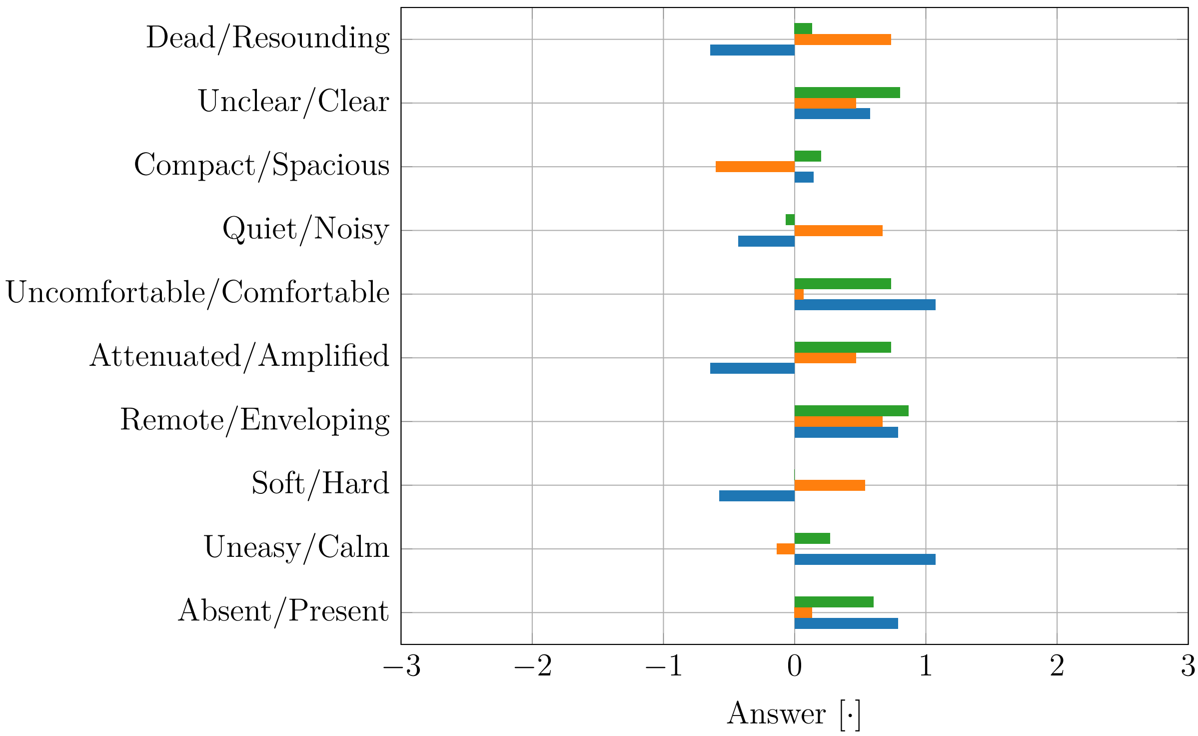


Figure 5.6: Bar plot of the mean answer from all respondents in the sound segment. The rooms are bedroom (●), kitchen (●), living room (●).

To find the factors behind the answers an EFA is used again. Three significant factors were found explaining 70 percent of the variance. The loadings of each factor can be seen on table 5.1. Because there are three factors the loading plots and score plots have been kept out but can be found in figure M.28 in the appendix.

	Factor 1 (31.61%)	Factor 2 (15.08%)	Factor 3 (25.26%)
Dead/Resounding	**-1.08**	-0.13	-0.29
Unclear/Clear	0.03	**0.79**	0.08
Compact/Spacious	-0.03	0.11	**0.50**
Quiet/Noisy	**-0.88**	-0.05	-0.13
Uncomfortable/Comfortable	0.21	0.32	**0.60**
Attenuated/Amplified	**-0.91**	0.25	-0.24
Remote/Enveloping	-0.17	**0.64**	0.03
Soft/Hard	-0.35	-0.08	**-0.94**
Uneasy/Calm	0.35	0.00	**0.89**
Absent/Present	0.27	**0.53**	0.29

Table 5.1: FA loadings for sound segment.

Factor 1 is based on dead/resounding, quiet/noisy and attenuated/amplified. This could be interpreted as the feeling of reverberation in a room. **Factor 2** is based on unclear/clear, remote/enveloping and absent/present. Absent/present has a low loading and could be discarded. The factor could be interpreted as the feeling of spaciousness. **Factor 3** is based on soft/hard, uneasy/calm, uncomfortable/comfortable and compact/spacious. Uncomfortable/comfortable and compact/spacious could be discarded because of a low loading. The factor could be interpreted as the feeling of pleasantness.

The sounds influence on rooms can thereby be defined by three factors: reverberance, spaciousness and pleasantness. This is interesting as the subjective opinion is three dimensional while the objective parameters are two dimensional. This will be further analysed in the next chapter.

The comfort segment scales are either normal distributed or single-side distributed. The mean answer to the comfort segment for each room can be seen on figure 5.7. From the mean answers it can be seen that some scales such as sleepy/awake and enclosed/open have characteristics comparable to those of dead/resounding and soft/hard. This could be a because they are correlated but the large difference in sleepy/awake argues that the comfort is more based on the purpose of the room (people sleep in their bedroom) than the room acoustics affecting comfort.

Two scales in the sound and comfort scales are identical but two different questions are asked. One of the scales is uncomfortable/comfortable. It can be seen that it for sound varies by approximately 1 while it varies with less than 0.4 for comfort. This suggests that the comfort level of respondents is not only affected by the room acoustics but by a range of variables. But this should also be expected.

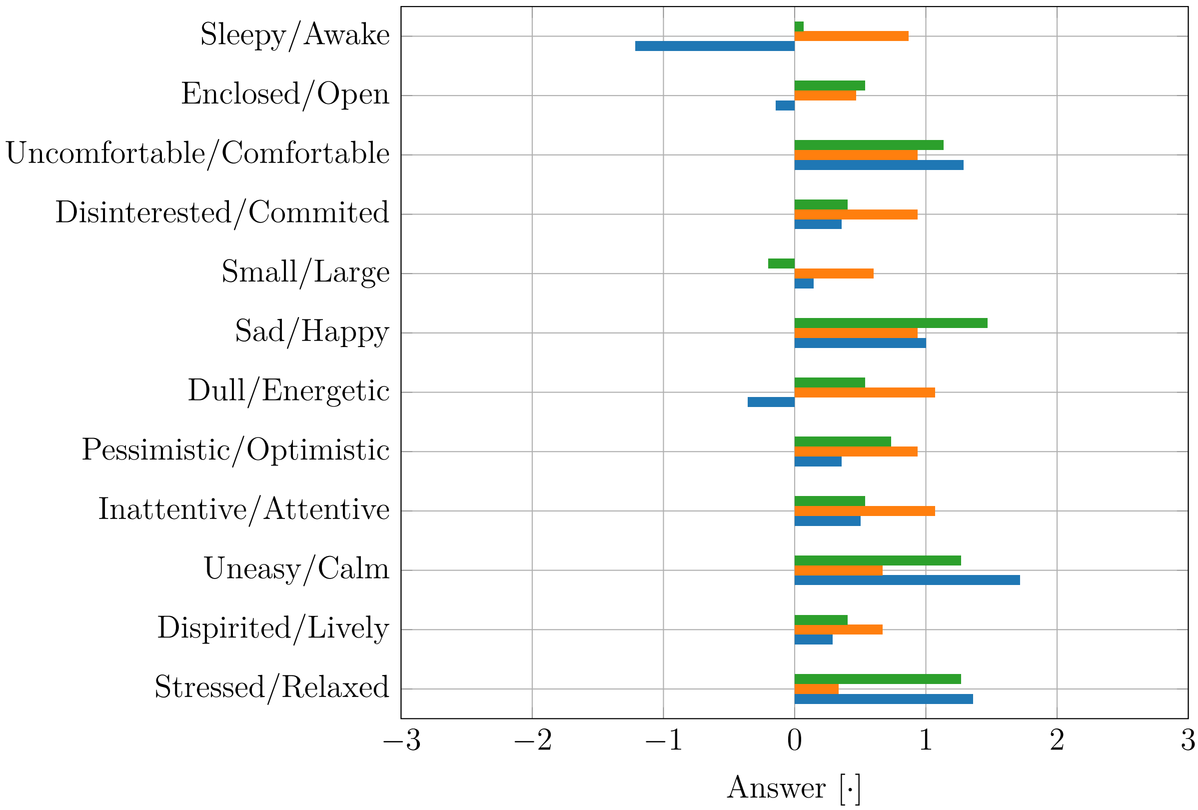


Figure 5.7: Bar plot of the mean answers from all respondents in the comfort segment. The rooms are bedroom (●), kitchen (●), living room (●).

Again the factors behind the answers are desired and found using EFA. Three factors were found explaining 69 percent of the variance. The loadings of each factor can be seen on table 5.2.

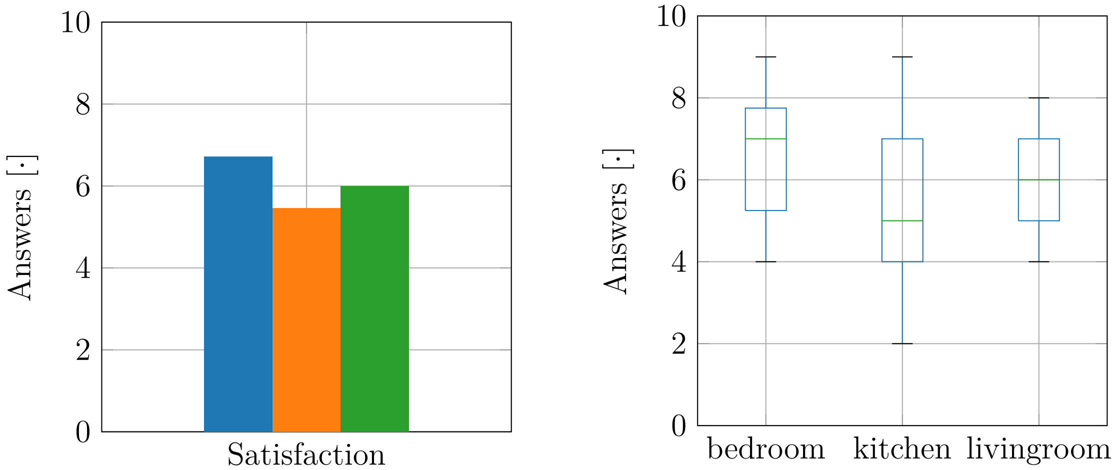
	Factor 1 (30.74%)	Factor 2 (24.06%)	Factor 3 (14.39%)
Sleepy/Awake	**1.40**	0.05	-0.11
Enclosed/Open	**0.67**	-0.28	-0.02
Uncomfortable/Comfortable	0.27	**-0.52**	0.05
Disinterested/Commited	0.29	-0.08	**-0.69**
Small/Large	0.22	-0.22	-0.27
Sad/Happy	0.29	**-0.70**	-0.07
Dull/Energetic	**0.75**	0.01	**-0.69**
Pessimistic/Optimistic	0.45	**-0.58**	-0.35
Inattentive/Attentive	0.36	-0.32	**-0.59**
Uneasy/Calm	-0.14	**-0.84**	0.02
Dispirited/Lively	0.20	-0.13	-0.43
Stressed/Relaxed	-0.24	**-0.91**	-0.13

Table 5.2: FA loadings for the comfort segment.

Because there are three factors the loading plots and score plots have been kept out but can be found in figure M.30 in the appendix. **Factor 1** is based on sleepy/awake, dull/energetic and enclosed/open with a heavy loading on sleepy/awake. The factor is interpreted as activity which is linked more to the use of the room than an acoustic trait as discussed earlier. **Factor 2** is based on stressed/relaxed, uneasy/calm, sad/happy, pessimistic/optimistic and uncomfortable/comfortable. The variables pessimistic/optimistic and uncomfortable/comfortable could be discarded because of a weak loading. The factor is interpreted as how content a respondent is. **Factor 3** is based on disinterested/committed, dull/energetic and inattentive/attentive. The factor is interpreted as interest.

The comforts of respondent can thereby be defined by three factors: activity, content and interest.

The last questionnaire segment which will be analysed is the satisfaction segment. The mean rating of each room and the distribution of all answers for each room can be seen on figure 5.8. The room which respondents dislikes the most is the kitchen as some respondents have rated the room acoustics as very unsatisfactory. The kitchen also has the largest spread of satisfaction. Because of the low sample size it cannot be concluded definitively if the bedroom is more satisfactory than the living room.



(a) Mean. **(b)** Box plot.

Figure 5.8: Satisfaction segment answers. The rooms are bedroom (●), kitchen (●), living room (●).

This concluded the individual data analysis. It has been shown that there is a large difference in results compared to earlier studies. The factors for objective parameters and subjective parameters have now been interpreted individually and the next chapter will try to interpret the correlation of them.

6 | Correlating Objective and Subjective Data

The purpose of this chapter is to use the individual assessments and find the overall meaning of the dataset. The factors interpreted from all the objective and subjective parameters are:

- Objective factors: reverberation, absorption.
- Sound factors: subjective reverb, spaciousness, pleasantness.
- Comfort factors: activity, content, interest.

Because the dataset is limited to 15 dwellings it is chosen to find meaning in the overall factors instead of the individual parameters. The conclusion should therefore be which subjective factors correlates with which objective factors and how they both correlate with satisfaction.

The first correlation is an EFA between the objective factors, the sound factors and the satisfaction rating. The correlation matrix can be seen in table 6.1. The overall correlation between the factors seems to be very low as the highest correlation is 0.31. The important thing to note is however how the individual factors are correlated.

	Reverberation	Absorption	Subjective Reverb	Spaciousness	Pleasantness	Satisfaction
Reverberation	**1.00**	0.02	-0.31	-0.22	0.17	-0.06
Absorption	0.02	**1.00**	-0.08	0.01	-0.23	-0.30
Subjective Reverb	-0.31	-0.08	**1.00**	-0.02	0.11	0.21
Spaciousness	-0.22	0.01	-0.02	**1.00**	0.04	0.18
Pleasantness	0.17	-0.23	0.11	0.04	**1.00**	0.28
Satisfaction	-0.06	-0.30	0.21	0.18	0.28	**1.00**

Table 6.1: Correlation Matrix for the objective factors, the sound factors and satisfaction.

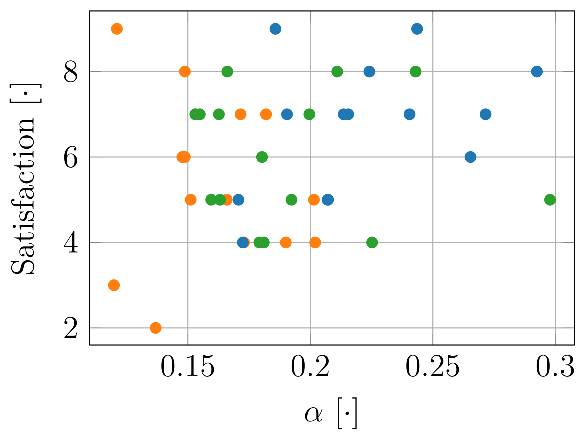
Three significant factors were found explaining 38 % percent of the variance. The reason for the low variance is caused by the low overall correlation and it could be discussed whether a factor analysis is the proper tool. Nevertheless the loadings for each of the three factors can be seen in table 6.2.

	Factor 1 (14.00%)	Factor 2 (15.91%)	Factor 3 (7.55%)
Reverberation	**0.70**	0.07	-0.20
Absorption	0.02	-0.43	0.02
Subjective Reverb	**-0.54**	0.28	-0.23
Spaciousness	-0.15	0.11	**0.58**
Pleasantness	0.15	**0.53**	-0.05
Satisfaction	-0.12	**0.63**	0.14

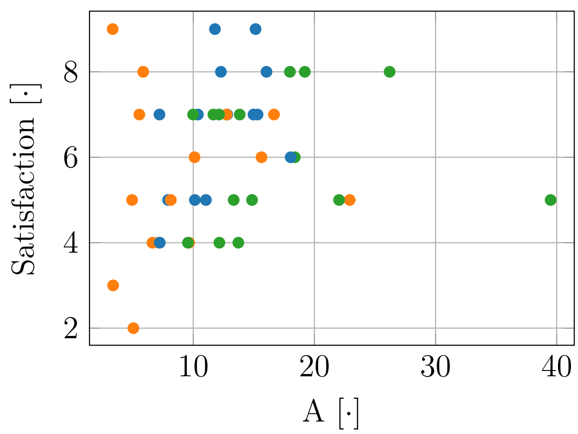
Table 6.2: Loading matrix.

Satisfaction is highly correlated with pleasantness and absorption and not reverberation and spaciousness. This means that the more sound energy the room absorbs the more pleasant the room is and thereby more satisfactory. Logically it makes sense that the satisfaction is not correlated with reverberation. As an example, if one is to walk into a very large room with a large reverberation time it is not necessarily perceived worse than walking into a small room with a low reverberation time. Reverberation time is strongly correlated with the subjective perception of reverberation but as explained it is not correlated with likeness of the room. The perception of spaciousness is not correlated with any of the other factors. This is probably due to not measuring any of spatial measures as they were discarded.

As satisfaction is highly correlated with the absorption factor scatter plots of the satisfaction as a function of average absorption and equivalent absorption area can be seen on figure 6.1



(a) Absorption



(b) Equivalent absorption area

Figure 6.1: Satisfaction vs parameters. The rooms are bedroom (●), kitchen (●), living room (●).

From the figures it is difficult to conclude that there is a clear correlation between satisfaction and absorption and equivalent absorption area. The reason for this is that some of the samples have a high satisfaction but a low absorption. Therefore it is deemed that more samples must be collected to classify likeness and thereby acoustic comfort using the absorption parameters. If one is to choose between which of the parameters should be used to classify based on the limited data, absorption seems to be more appropriate than equivalent absorption area based on equivalent absorption area being dependent on the volume.

The factors of the comfort segments are also correlated with the objective parameter factors and satisfaction. The correlation matrix can be seen in table 6.3. Again the correlations are low but the EFA is performed.

	Reverberation	Absorption	Activity	Content	Interest	Satisfaction
Reverberation	**1.00**	-0.01	0.27	-0.07	-0.08	-0.05
Absorption	-0.01	**1.00**	0.13	0.35	-0.04	-0.34
Activity	0.27	0.13	**1.00**	-0.00	-0.07	-0.06
Content	-0.07	0.35	-0.00	**1.00**	0.05	-0.20
Interest	-0.08	-0.04	-0.07	0.05	**1.00**	0.23
Satisfaction	-0.05	-0.34	-0.06	-0.20	0.23	**1.00**

Table 6.3: Correlation Matrix for the objective parameters, the comfort segment and satisfaction.

Two significant factors were found explaining 25 % of the variance. The loadings can be seen on table 6.4.

	Factor 1 (16.33%)	Factor 2 (9.62%)
Reverberation	-0.04	**0.54**
Absorption	**0.69**	0.04
Activity	0.12	0.47
Content	**0.50**	-0.14
Interest	-0.11	-0.19
Satisfaction	-0.48	-0.13

Table 6.4: Loading matrix.

From the loadings it can be seen that absorption and content are correlated while reverberation and activity are correlated. Interest is not correlated with any of the two. From the individual analysis it looked as the comfort parameters were strongly linked to the purpose of the room and weakly linked to room acoustics. If the activity level is high then according to the factors the reverberation time is also high. This fits with the bedroom having the lowest reverberation time and activity and the kitchen having the highest activity level and almost highest reverberation time.

To conclude on this analysis absorption was the factor most correlated with satisfaction. There was however not enough empirical data to base a classification on an objective parameter (α or A) from the absorption factor. More data is needed to do this. Based on the correlation matrices and explained variances one could question if a factor analysis was the best tool to use.

7 | Conclusion

This project has covered the subject of acoustic indoor comfort in dwellings. An in-depth literature study into the current standards and regulations for room acoustics in Denmark has been performed where it was determined that there are no regulations for acoustic comfort if noise is not considered. The standards and regulations simply did not state any numbers for domestic rooms. Furthermore it was concluded that the classification of reverberation time in DS 490 did not reference any source validating the numbers. The most documented and properly classified area within room acoustic is noise and noise annoyance.

A literature study of current used acoustical parameters in both domestic rooms and performance spaces has furthermore been conducted as the literature concerning domestic rooms is very sparse. The study revealed that reverberation time is the most common parameter for all environments such as domestic rooms and performance spaces. For performance spaces several descriptors are defined based on the room impulse. These parameters however are highly dependent on being measured in a large room e.g. concert halls, as the parameters in domestic sized rooms are completely correlated with reverberation time.

An investigation into the current room acoustical state of domestic rooms in dwellings in Denmark has been performed. No solution to obtain fast and proper documented ISO 3382-2 room impulse measurements was available, a proprietary measurement program was therefore developed to obtain a database of room impulses. The measurement program allowed for very efficient ISO 3382-2 precision method measurements. Using this program a database of 45 rooms from 15 different dwellings have been acquired throughout a period of 1 week. From analysis of the reverberation times measured it showed a worsening compared with previous studies. The current state of furnished dwellings in Denmark shows a trending characteristics towards unfurnished dwellings, meaning the current inventory in dwellings are very poor acoustic absorbers.

To accompany the objective measurements, a questionnaire has been developed. The questionnaire has been used to describe the acoustic comfort within the dwelling and have been used to correlate objective parameters with a subjective likeness of the dwelling.

From the objective and subjective data multiple factor analysis have been performed. The analysis showed that current regulations, which specifies its classification in reverberation time, is a bad solution. The subjective feeling of acoustical satisfaction correlated more with the absorption in the room. This correlation ultimately states that the desired reverberation time scales according to the volume of the room suggesting that the optimal reverberation time is based on an assumption of how the reverberation should be and not an absolute value.

A Proposal for a classification system for the acoustic comfort in domestic rooms could not be created. From the analysis of subjective and objective data it could be concluded that more data was required for creating a plausible classification.

8 | Future Work

From the results achieved in the analysis it is clearly seen that a lack of data hindered the development of a classification scheme. With a much larger dataset it would have been possible to ensure both a diverse enough dataset, more confidently determine underlying factors and develop the classification.

As no literature, to the authors knowledge, have correlated subjective and objective room parameters it is not certain that multiple factor analysis is the most suitable analysis tool. The option for using multi dimensional scaling (MDS) could be viable, but has not been further investigated.

From the analysis it can also be seen that a rework of the questionnaire is suitable. A proper word elicitation would ensure that all potential parameters are discovered and redundant scales discarded.

If the measurements were to continue, precision within building information must be improved. From the preliminary results achieved in this project it is seen that absorption correlates more with acoustical satisfaction than the absolute reverberation time. The absorption parameter is however very dependent on correctly measured volumes. Volume estimation should therefore receive emphasis and approximated rectangular shapes should be changed to also represent random shaped rooms, as outliers were found because of bad volume estimation.

Several measurements beside measuring the impulse response could be performed. Measurements such as direct STI ensuring all non-linear information is captured within the STI. Spatial parameters such as Lateral Energy Fraction or Inter Aural Cross Correlation could also be added as spaciousness was a factor in perception. Finally measurements like binaural recordings would also improve the database if potential validation experiments are to be performed.

With preliminary analysis showing current ISO 3382-1 performance parameters being poor at describing domestic rooms it will be ideal to investigate new boundaries for these measurements, adjusting them to work in domestic sized volumes.

Finally the correlation between furnished and unfurnished room has in this project not been investigated. As the characteristics of measured dwellings resembles that of and unfurnished room it would be interesting to determine the effect of current modern furniture by also measuring the rooms unfurnished.

9 | Perspective

With the projects current state, it is not possible classify acoustic comfort, but as the analysis show a much higher correlation with absorption rather than reverberation time, determining a classification that actually supports acoustic comfort is plausible. By determining acoustic comfort in a way which would satisfy peoples room acoustical needs a better living quality could be achieved. Combining larger surveys of the same kind, in conjunction with research projects like REBUS [Larsen et al., 2017], it would aid the designers of newer buildings and houses to build acoustic pleasant rooms. Also with a definition of acoustic comfort it would open a discussion on changing current standards and provide literature with supporting claims for a classifications.

If the database is expanded to contain detailed room characteristics such as window size, furniture description etc. much more advanced analysis could be performed increasing the depth of conclusions significantly. This would however probably require collaboration with other research fields such as civil engineering.

A classification of acoustical comfort could be structured in several different ways. Disregarding which parameter should be used. First of all it must be decided if the classification should be based on unfurnished or furnished rooms. If the classification is based on unfurnished rooms it could be based on how much absorption the furniture needs to posses. A class A could for example mean that all types of furniture would be acceptable for the acoustic comfort, while lower classes would specify more strict furniture designs in order for the acoustic comfort to be acceptable.

If the classification was based on furnished rooms a more straightforward scheme could be used based on a single parameter value. A class A could for example mean that the room was designed for listening test and a lower class would mean that listening would become harder. A scheme such as this is reminiscent of the STI ranking.

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Part II

Appendix

A | Room acoustical parameters

This appendix will examine which room acoustical parameters can be found in literature used for various purposes such as living, performance etc. in order to establish an overview. A room acoustical parameter in this project is defined as:

A number or quality derived from measurements which describes an objective quality of a single room.

Being that many different parameters are defined in various articles, books and standards throughout, only parameters which are either standardized, have been or are commonly used, are selected for examination as it is important for the project to use widely regarded parameters. The following standards and recommendations will be used for examining parameters:

ISO 3382-1:2009 - Measurement of room acoustic parameters - Part 1: Performance spaces describes the method for measuring reverberation time with respect to other acoustical parameters in performance spaces. Furthermore it defines said acoustical parameters and mentions both just noticeable difference (JND) and typical range. These values are however stated with respect to a 25.000 m^3 empty multi purpose hall. The standard specifies two methods of measuring the reverberation time, being either interrupted noise method or integrated impulse response method. If room acoustic parameters other than the reverberation time are to be determined only the latter method is relevant, as these parameters are based on the impulse response.[ISO 3382-1, 2009]

IEC 60268-16:2011 - Objective rating of speech intelligibility by speech transmission index describes the method for measuring and calculating the speech transmission index (STI) for different applications. Furthermore it describes the applicability of STI in different scenarios [IEC 60268-16, 2011]. Two method exist, direct and indirect, which is either based on actual recordings of a specific signal or post processing using the impulse response.

ITUR-R BS.1116-3 - Methods for the subjective assessment of small impairments in audio systems describes the method for evaluating loudspeaker performance. Despite the main purpose of this recommendation regards loudspeaker evaluation it also specifies recommendation for the room used under testing. The recommendation provides considerations regarding room dimensions and reverberation time [ITU-R BS.1116-3, 2015].

IEC60268-13: Sound system equipment - Listening tests on loudspeakers describes methods for evaluating loudspeaker performance. The main purpose of this standard concerns loudspeaker evaluation, however the standard provides considerations regarding room dimensions and reverberation time [IEC 60268-13, 1998].

A.1 | Performance space parameters

The ISO 3382-1 specifies a variety of different parameters with respect to performance spaces. Being that a domestic room found in dwellings and a performance can differ a lot in volumes, not all parameters can be applicable to the small room. However in some scenarios a small room can, to some extend, be seen as a performance space, e.g. having one or more people talking/listening. [ISO 3382-1, 2009]

Reverberation Time

The Reverberation time is the time, expressed in seconds, that would be required for the sound pressure level (SPL) to decrease 60 dB from a level 5 dB below an initial steady state SPL. This is denoted as T_{60}. Three derivations of T_{60} has been created, as 60 dB SNR can be hard to achieve in large spaces or noisy environments. These are called T_{30}, T_{20} and the Early Decay Time(EDT). All four parameters are described briefly below

T_{60} is the time between -5 dB and -65 dB. The decay curve must be linear above -65 dB.

T_{30} is the time between -5 dB and -35 dB multiplied by 2. The decay curve must be linear above -35 dB.

T_{20} is the time between -5 dB and -25 dB multiplied by 3. The decay curve must be linear above -25 dB.

EDT is the time between 0 dB and -10 dB multiplied by 6.

Throughout history the reverberation time has been the most common measure for evaluating room acoustics. Firstly because of the equipment availability such as tape recorders etc. did not allow for more intricate measurements such as impulse responses [Jackson and Leventhall, 1972]. Secondly, being that reverberation time has been the "go-to" parameter, having this parameters makes for more comparative data[Díaz and Pedrero, 2005]. The main issue is the lack of linkage between reverberation time and what can be deemed agreeable for living conditions [Vanwelkenhuysen, 1972]. This is to be compared with EDT, which shows to relate more to perceived reverberance while T-times relates more to a physical property of the room[Rossing et al., 2015].

Very few states recommended values for reverberation time, but some international standards have done so in correlation with listening room recommendations. The ITU-R recommendations are of interest, given that the primary aim of said recommendation was to create ideal conditions for hearing small impairments on different codecs [ITU-R BS.1116-3, 2015]. Furthermore the IEC requirements for a listening room were created to simulate the average consumers living room [IEC 60268-13, 1998]. From IEC 60268-13 a specific frequency dependent reverberation time is given, the requirement for said time can be seen in figure A.1. For comparison, the mask given for the ITU-R BS.1116-3 requirement is also shown.

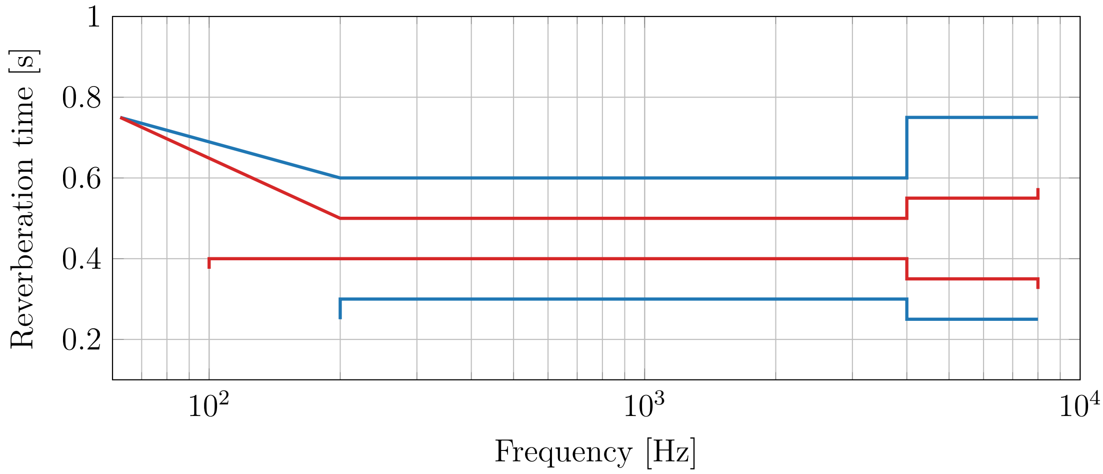


Figure A.1: Reverberation time tolerance mask. Note that IEC is constant, while ITU-R shifts according to T_m (●)[IEC 60268-13, 1998], (●)[ITU-R BS.1116-3, 2015]

The ITU-R BS.1116-3 specifies the desired reverberation time T_m according to the room volume, and is stated in eq. A.1 [ITU-R BS.1116-3, 2015].

$$T_m = 0.25 \cdot \frac{V}{V_0}^{1/3} \tag{A.1}$$

where:

V is the volume of the room $[m^3]$

V_0 is a reference volume of 100 $[m^3]$

Both ITU-R and IEC specifies a fairly identical reverberation time suitable for listening experiment. These values may be in the vicinity for a high class requirement, As they and used for listening test requiring proper acoustical conditions. The IRU-R recommendation mask seems more strict, which is most likely derives from it begin used to listen for small impairments in codes whereas the IEC is defined to be more fitting for the reverberation of a regular living room.

Equivalent absorption area and absorption

A parameter which is linked to reverberance is equivalent absorption area denoted A which take into account the volume of the room. The equivalent absorption compensates for the size of the room by scaling the reverberation time according to eq. A.2. This parameter shows if the reverberation is high relative to the size of the room [Kuttruff, 2016].

$$A = \frac{0.16 \cdot V}{T} \tag{A.2}$$

Alternatively the absorption α in a room will display how efficient the room is to absorb sound. The absorption parameter can be determined by eq. A.3 by dividing the equivalent absorption area with the surface area S of the room.

$$\alpha = \frac{A}{S} \tag{A.3}$$

Sound Strength

The parameter sound strength (G), states the sound level in the real room in relation to the sound level in an free field environment with the same sound source [Goldstein, 2010]. The sound strength is given as the logarithmic ratio of two said sound levels and are defined as follow:

$$G = 10 \cdot \log_{10} \frac{\int_0^\infty p^2(t)dt}{\int_0^\infty p_{10}^2(t)dt} [dB] \tag{A.4}$$

where $p(t)$ is the impulse response at the measurement position using an omni-directional source, $p_{10}(t)$ is the impulse response at 10 m distance in free field. The measurement demonstrates how the rooms reflections effect the sound level. The recommended value for strength varies depending on both music scheme and listener. The ISO 3382-1 states that just noticeable difference is 1 dB and is typically in the range of -2 dB to +10 dB. In most existing concert halls it is usually around 3 to 5 dB in the midrange frequencies in the audience [Goldstein, 2010].

Clarity Measures

Clarity is used to define the balance between sound energy in early reflection with those that arrive later. A high clarity will result in the sound perceived being more clear, since most energy is present at the incident wave and not in the reverberant part. It is given as the logarithmic ratio of two said energy levels. Different methods exist for defining clarity exist and it is further defined for both music and speech, where music is defined as the first 80 ms and speech being 50 ms. They are defined as [ISO 3382-1, 2009]:

Clarity (C_{80}) for music:

$$C_{80} = 10 \cdot \log_{10} \frac{\int_0^{80\ ms} p^2(t)dt}{\int_{80\ ms}^\infty p^2(t)dt} [dB] \tag{A.5}$$

Clarity (C_{50}) for speech:

$$C_{50} = 10 log_{10} \frac{\int_0^{50\ ms} p^2(t)dt}{\int_{50\ ms}^\infty p^2(t)dt} [dB] \tag{A.6}$$

where $p(t)$ is the impulse response at the measurement position.

Alternatively for speech, Definition (D_{50}) can be used, which compares the sound energy in early sound reflections with all reflections. It is defined as the ratio of the energy in the first 50 ms of the impulse response compared to the energy in the entire impulse response.

$$D_{50} = \frac{\int_0^{50\ ms} p^2(t)dt}{\int_0^{\infty} p^2(t)dt} \tag{A.7}$$

where $p(t)$ is the impulse response at the measurement position. The relation between C_{50} and D_{50} is defined as,

$$C_{50} = 10log_{10}\frac{D_{50}}{1 - D_{50}}[dB] \tag{A.8}$$

Finally centre time can be used, which is the time of the centre of gravity of the squared impulse response. A high value is an indicator of poor clarity. It is defined as,

$$T_s = \frac{\int_0^{\infty} tp^2(t)dt}{\int_0^{\infty} p^2(t)dt}[s] \tag{A.9}$$

where $p(t)$ is the impulse response at the measurement position. As opposed to both clarity and definition, centre time avoids dividing into early and late periods. This is useful de-emphasising the impact from positioning, should one be more interested in the room as a whole instead of specific positions, e.g. an entire hall compared to individual seating [Bradley, 2011]. The ISO 3382-1 sets the following values for clarity measures:

- C_{80} has a noticeable difference of 1 dB and is typically in the range of -5 dB to +5 dB
- D_{50} has a noticeable difference of 0.05 and is typically in the range of 0.3 to 0.7
- T_S has a noticeable difference of 10 ms and is typically in the range of 60 ms to 260 ms

Lateral Energy Fraction

Lateral Energy Fraction (LF) is a description of how much energy there is in the side reflection in relation to all the energy. This parameters is divided into both an early and late measure. The difference between being that early accommodate the first 5 to 80 ms and late covers the remaining time beyond 80ms. [ISO 3382-1, 2009]

$$\text{Early}_{LF} = \frac{\int_{5\ ms}^{80\ ms} p_L^2(t)dt}{\int_0^{80\ ms} p^2(t)dt} \tag{A.10}$$

$$\text{Late}_{LF} = 10 \cdot log_{10}\frac{\int_{80\ ms}^{\infty} p_L^2(t)dt}{\int_0^{\infty} p_{10}^2(t)dt}dB \tag{A.11}$$

where $p_L(t)$ is the impulse response at the measurement position with a microphone having a figure-of-eight directivity pattern and $p(t)$ is the impulse response at the measurement position with an omni-directional microphone. $p_{10}(t)$ is the impulse response measured at distance of 10 m in a free field. LF describes what is perceived as the width of the sound source. The ISO 3382-1 specifies the JND to 0.05 with a typical range of 0.05 to 0.35.

Inter Aural Cross Correlation

Inter Aural Cross Correlation (IACC) utilizes either a dummy head or real head with microphones at the ear canals, when measuring. An IACC yields a value ranging from -1 to +1. A value of -1 means the signals are identical, but completely out of phase. +1 means they are identical, and 0 means they have no correlation at all. The IACC will be nearly +1 for mono sources directly in front of or behind the listener, with lower values if the source is off to one side. IACC is defined as [ISO 3382-1, 2009]:

$$IACF = \frac{\displaystyle\int_{t_1}^{t_2} p_l(t) p_r(t+\tau) dt}{\sqrt{\displaystyle\int_{t_1}^{t_2} p_l^2(t) dt \cdot \int_{t_1}^{t_2} p_r^2(t) dt}} \tag{A.12}$$

where $p_l(t)$ is the impulse response at the left ear, $p_r(t)$ is the impulse response at the right ear.

$$IACC_{t_1 t_2} = max|IACF_{t_1 t_2}(\tau)| \ \ ,for - 1 \ ms < \tau < +1 \ ms \tag{A.13}$$

Both LF and IACC can be used to determine the perceived width of a sound source, having significant correlation at lower frequencies (125 Hz to 1000 Hz) but deviates at frequencies above, this effect can be related to the characteristics of the human pinna [de Vries et al., 2001].

Room Dimensions

Room dimension is not a specific acoustical parameter as it is a physical parameter, however the room dimension still play an important role at low frequencies. It is known that due to the boundaries of a room, standing waves appear. The frequencies, modal frequencies or eigenfrequencies, at which this happens can easily be determined for simple rectangular shaped rooms by equation A.14 [Kinsler et al., 1999].

$$f_n = \frac{c}{2}\sqrt{\left(\frac{n_x}{l_x}\right)^2 + \left(\frac{n_y}{l_y}\right)^2 + \left(\frac{n_z}{l_z}\right)^2} \tag{A.14}$$

n is the room mode

l is the length(x), width(y) or height(z)

The frequency area at which the modal frequencies will be the dominant factor [Toole, 2017] for sound are defined by the Schroeder Frequency, f_c and is defined by equation A.15 [Schroeder, 1996].

$$f_c = 2000 \cdot \sqrt{\frac{T}{V}} \tag{A.15}$$

T is the T_{60} reverberation time [s]

V is the volume of the enclosure [m^3]

It is desirable to have an even as possible distribution of these frequencies throughout the room. Such a distribution will even out the effects of potential distinct modes, giving the best conditions for listening in the room [Bech and Zacharov, 2006]. The IEC 60268-13 specifies how a rooms dimensions should be in order to achieve said modal distribution, given in eq. A.16.

$$\frac{w}{h} \leq \frac{l}{h} \leq (4.5 \cdot \frac{w}{h} - 4) \qquad \frac{w}{h} < 3 \qquad \frac{l}{h} < 3 \tag{A.16}$$

where:

l is the length of the room [m]

h is the height of the room [m]

w is the width of the room [m]

Furthermore, it is advised to have a floor area for monophonic and two-channel stereophonic reproduction within the range of 25–40 m^2 and within 30–45 m^2 for multichannel reproduction [IEC 60268-13, 1998].

Correlation between parameters

The parameters above, all from ISO 3382-1, describe different attributes for sound in the room, but the correlation between each parameter is relatively high [Pelorson et al., 1992]. When measured in large performance spaces, 3000 m^3- 21.000 m^3, a strong correlation persist. The correlation between the parameters discussed can be seen in table A.1.

	T	EDT	C_{80}	D_{50}	G	T_s
T	**1**					
EDT	0.56	**1**				
C_{80}	-0.3	-0.88	**1**			
D_{50}	-0.34	-0.83	**0.93**	**1**		
G	-0.34	-0.84	**0.98**	**0.97**	**1**	
T_s	0.55	**0.94**	**-0.95**	**-0.94**	**-0.94**	**1**
LF	0.03	0.23	-0.25	-0.27	-0.25	-0.22

Table A.1: Correlation matrix between room parameters for rooms with a size ranging from 3000 m^3 - 21.000 m^3 [Pelorson et al., 1992].

The high correlation between some of the parameters implies that selecting all parameters to describe a room would result in a redundant set of descriptors. As a measure of reverberance EDT should be considered as this is closest to what is perceived as reverberance. However a standard T_{20} or T_{30} measurement is useful for evaluating physical properties of the room and allows comparison of already known research.

From table A.1 it shows that one clarity measure is sufficient as the correlation between each is high. It can however, at this state, not be determined which type of measure is suitable. The question regarding choice of clarity measures lies within choosing either centre time or definition over clarity for speech or music. Studies show that centre time and definition correlate well with decay times, again cnf. with table A.1, hence describing reverberance more than clarity [de Vries et al., 2001]. However using definition or centre time has advantage of using no distinct time window between early and late energy [Rossing et al., 2015].

Both IACC and LF shows more relevance for performance spaces describing attributes that reflect upon performances like concerts, speeches and alike. These parameters are less important for evaluating dwellings as these values can be used to describe the width and spaciousness of the sound coming from a stage.

The considerations above are based on the large volumes specified in table A.1 and the correlations could deviate significantly when measuring in domestic rooms.

A.2 | Speech Transmission Index

The speech transmission index (STI) is used as a way of judging the intelligibility of speech without doing time consuming and costly psychophysical experiments. The aim is to estimate what can be seen as the effective SNR between speech and background noise. This is done by using what is known as the Modulation Transfer Function (MTF). MTF is used to describe the dynamic range, or lack of dynamic range, through a given transmission channel [Schroeder, 1981]. Adapting the MTF to focus on audible frequency bands it is possible to calculate an index which correlates well with subjective intelligibility [Steeneken and Houtgast, 1980]. It has shown that longer reverberation time and higher background noise results in a smaller MTF, i.e. lower STI, resulting in a poor intelligibility. [Steeneken and Houtgast, 1982]

STI is defined as 7 discrete frequency octave bands, from 125 Hz to 8 kHz, each containing 14 modulation frequencies, resulting in a total of 98 different frequencies.It is further divided into three subgroups, A Full STI (FULL STI), one for Public Address Systems (STIPA) and one for telecommunication (STITEL). A fourth type, the Room Acoustic STI (RASTI), has previous been used, but has of 2011 become obsolete since STIPA provides better results when used in electro-acoustic situations [van Wijngaarden et al., 2012]. The difference between RASTI and STIPA is a trade off regarding octave bands and modulation indices. The difference being as described below:

FULL STI uses all modulation indices, bringing the total amount of indices to 98.

STIPA uses two modulation indices, bringing the total amount of indices to 14.

STITEL uses one modulation indices, brining the total amount of indices to 7.

RASTI uses four and five modulation indices, but with only two bands (500 Hz and 2 kHz). Brining the total amount of indices to 9.

These three subgroups can be determined in two different ways, either direct or indirect.

Direct is the most comprehensive method where the MTF is determined by recording the modulation indices played into the room. Each frequency should have a length of 10-15 sec. The SPL should be adjusted to fit the specific situation, e.g. a speaker talking could be roughly 60 dB @ 1 meter. The advantage of direct method is the incorporation of all non-linear artefacts from the room.

The indirect method relies on the measured impulse response in the room. By extracting both SNR and reverberation time from the impulse, the STI can be determined as stated in eq. A.17. This is valid only for LTI-systems. When using the indirect method it is recommended to calculate the full STI.

$$m(f_m) = \frac{1}{\sqrt{1 + (\frac{2\pi f_m T}{13.8}^2)}} \cdot \frac{1}{1 + 10^{-SNR/10}} \tag{A.17}$$

Where f_m is the modulation frequency, T is the reverberation time in seconds and SNR is the signal-to-noise ratio [IEC 60268-16, 2011]. The STI is a useful parameter to describe ineligibility within a room, however it has showed to be overly pessimistic towards the actual results. Research has shown that to provide better estimations when performing the direct method the use of binaural recordings and selecting the better ear for evaluation is more accurate [van Wijngaarden and Drullman, 2008]. The binaural recording compensates for undesired reflections from the surroundings due to the shape of the pinna. These measurements has however not been standardized yet, but are currently being researched. The IEC 60268-13 does not specify any recommended values [IEC 60268-16, 2011].

B | Building Acoustics Measurement Program Interface

The purpose of this appendix is to document all the functions built into the BAMPI program. The appendix will cover each tab, describing how to menu works and what considerations have been made. The source code can be found on the enclosed CD in the `SourceCode`-folder. No compiled executable exist at this point and a python environment is needed to run the program. The program can be started by executing `main.py` assuming all the required dependencies are installed.

B.1 | The Main Menu

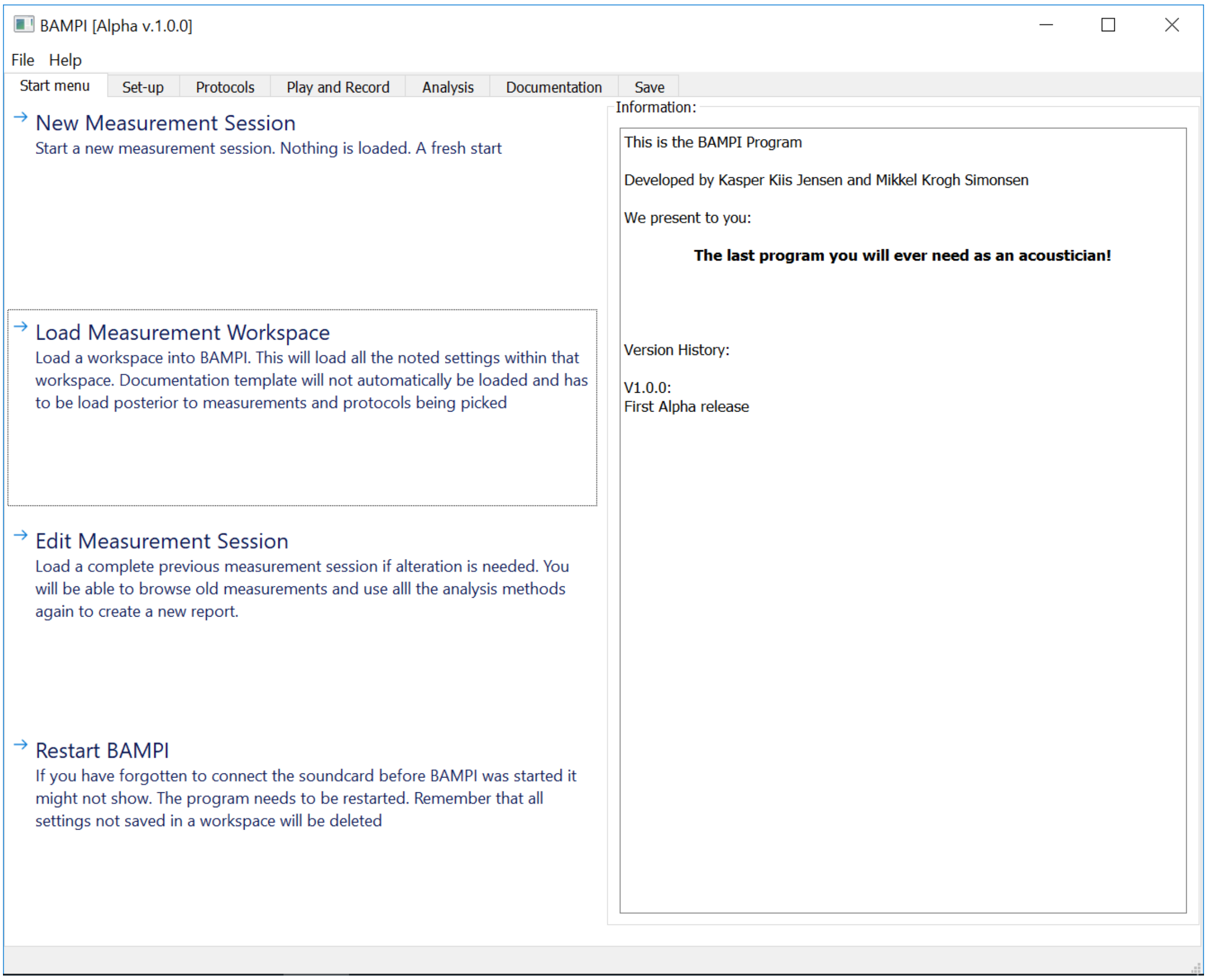


Figure B.1: The start-up screen of BAMPI.

The first screen showing when BAMPI is started is the main menu, the main menu allows the user to easily access the main features of the program. The four functions are described below

New Measurement Session If a new session is to be started. The system will detect all available sound cards and prepare the user for selection of the desired settings.

Load Measurement Session If the user already have a saved workspace ready for measurement it will be possible to load these as well. By loading a workspace everything will be set as saved by the user. This ensures that calibrated values for the sound card and equipment are set.

Edit Measurement Session If a user already have a measurement session done and want to perform different analysis method it is also possible to load saved measurements. It will not be possible to do new measurement when a complete measurement session has been loaded.

Restart BAMPI If the session is to be cleaned from all user settings it is possible to reset all settings and restart the program.

B.2 | Setup Menu

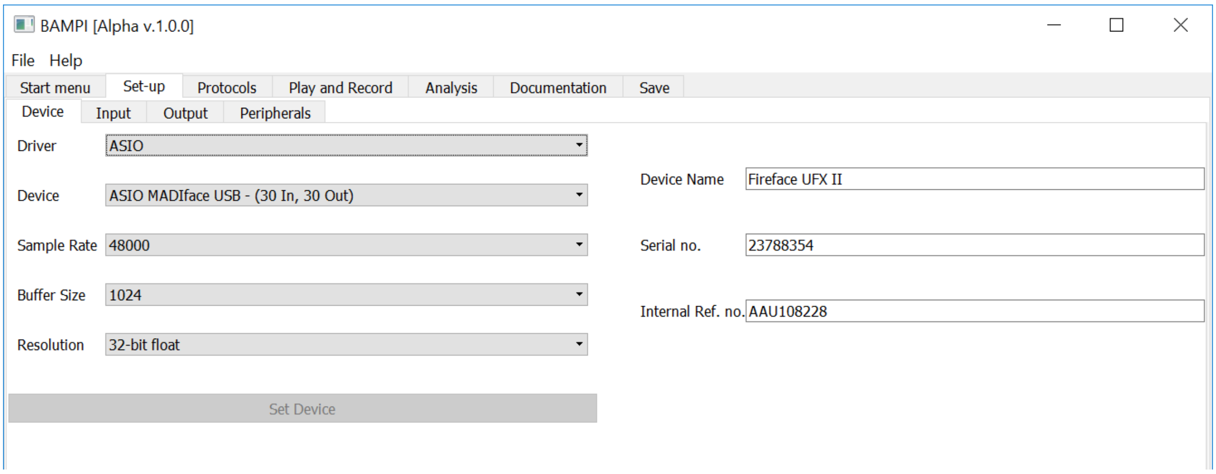


Figure B.2: Crop of the device setup menu in BAMPI.

Within the setup menu of BAMPI it is possible to determine which kind of drivers to use. The program will then show all available devices with those drivers, along with their respective sampling rate, buffer size and recording resolution. When the devices has been select it is optional if it is named or noted with serial no. and internal reference no. All the settings in this menu will automatically be documented when the measurement session is saved. When the device is selected it will automatically setup all channels and prepare for the user to configure the measurement system.

B.3 | Input and Output Selection

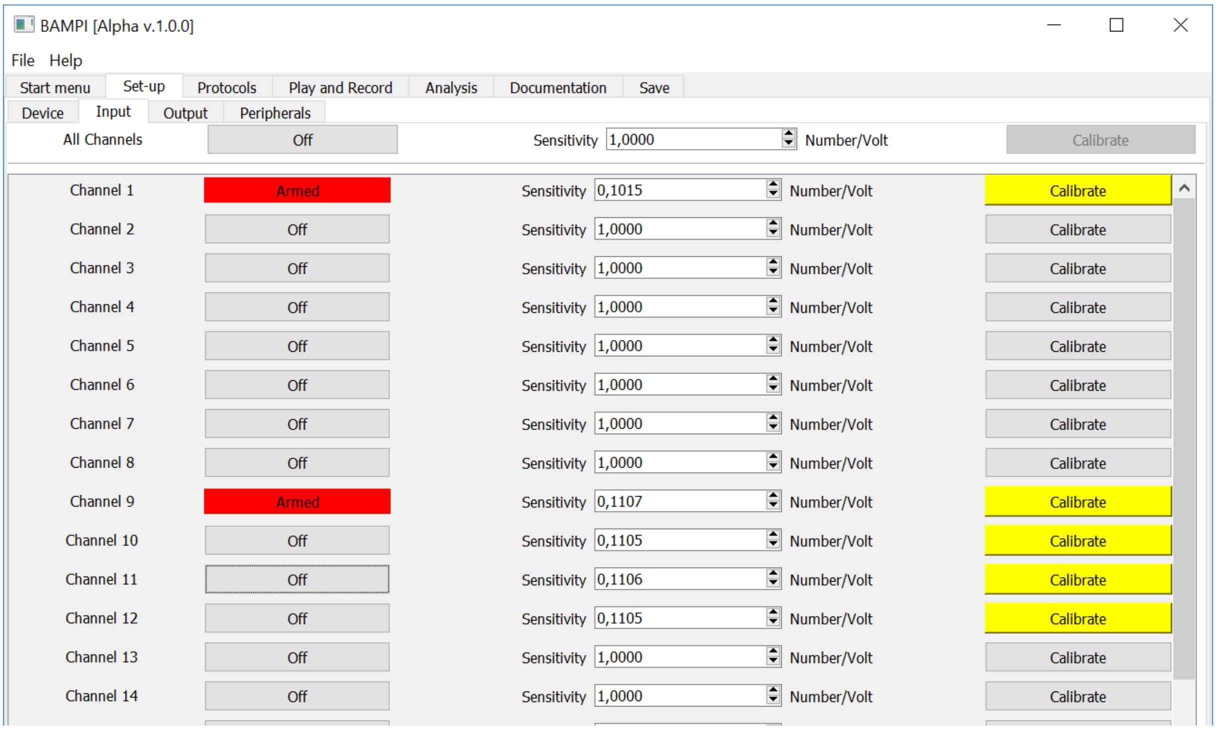
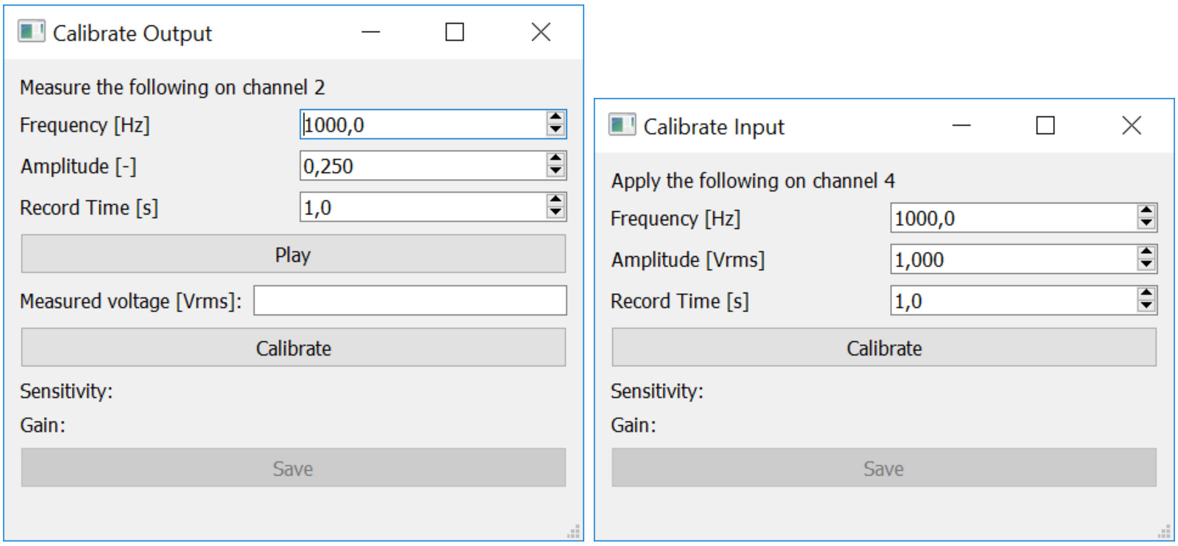


Figure B.3: Input menu in BAMPI.

On figure B.3 the input selection menu is shown, which is identical to the output menu as well. The input selection allows for the user to select the desired channels which should be armed for recording. For each channel it is possible to perform a calibration where a known voltage is applied to an input of the device and the measured number within the sound card is then adjusted to fit the voltage.

The calibration method for input channels, shown in figure B.4b, records for a user defined amount of time and determines amplitude of the signal in frequency domain. In frequency domain the signal is normalized by the length of the signal, ensuring the same energy for 1 sec recording as 10 seconds. By determining the amplitude in frequency it will suppress any additional noise on the recorded signal such as ventilation noise or sporadic sound events since it will only focus on the user defined frequency.

When calibrating the output, a signal from the sound card, shown in figure B.4a, will be supplied. The sound card will supply a known sinusoidal signal with a given amplitude defined by the user. The user will then record the signal using a measurement device of their choosing. The measured voltage is noted into the program and the BAMPI system will adjust accordingly.



(a) Window for output calibration. **(b)** Window for input calibration.

Figure B.4: Screenshot of the input and output calibration windows used in BAMPI.

B.4 | Peripheral Menu

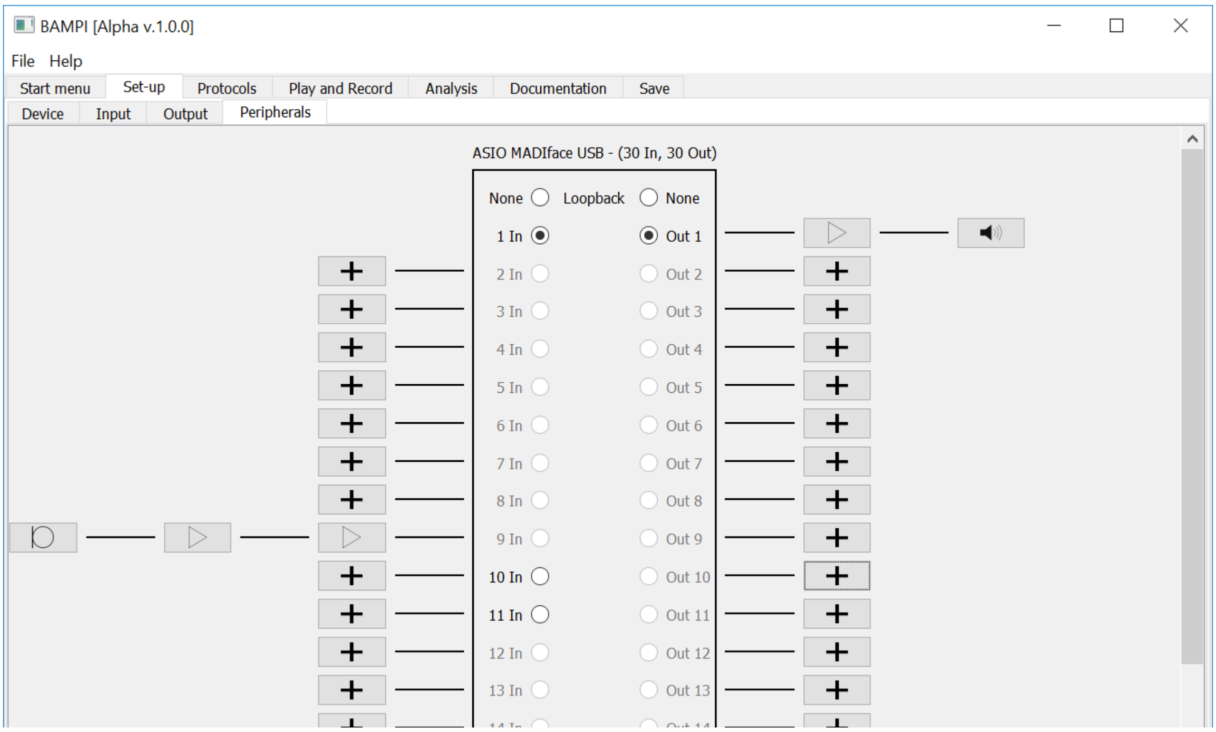
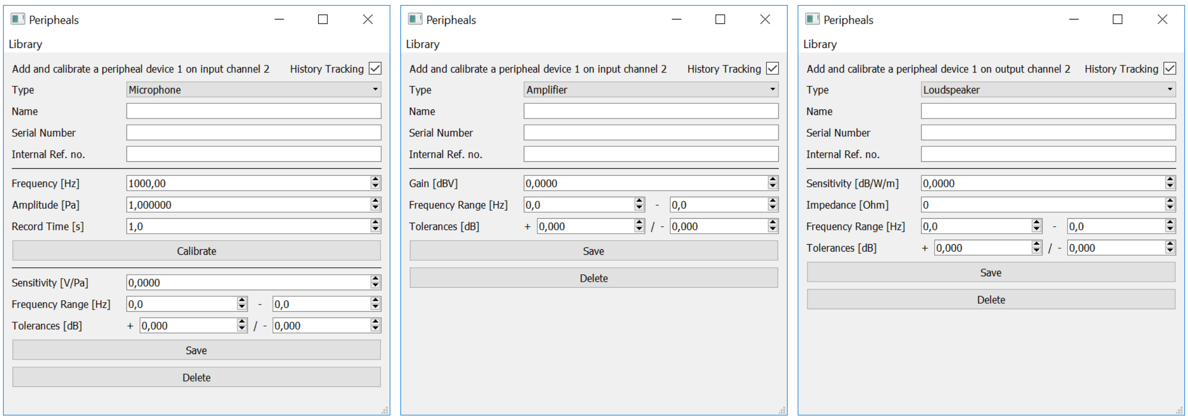


Figure B.5: Peripheral menu in BAMPI.

The BAMPI program handles all external peripherals which could be added to the measurement chain. There is an option for adding additional peripherals like microphone pre-amps, AD/DA-converters, loudspeakers or headphones. Each peripheral can be defined with a gain or sensitivity which is then accounted for in the measurement chain. The system allows for calibration of microphones using same procedure as for the input channels except this procedure requires an acoustical calibrator and not a voltage source.

The peripheral section allows for connection of a loopback signal from output to input which is used as a reference signal for impulse extraction. The loopback signal will ensure that the delay introduced in the sound card and its characteristics are removed in any deconvolution.



(a) Microphone selection. **(b)** Amplifier selection. **(c)** Loudspeaker selection.

Figure B.6: Additional peripherals that can be added to the measurement chain.

B.5 | Protocols

The BAMPI protocol tab have two protocols implemented in the current version. The first protocol covers background measurements which are used in conjunction with project REBUS and will not be covered further. The second protocol covers the ISO 3382-2 standard and can be seen on figure figure B.7.

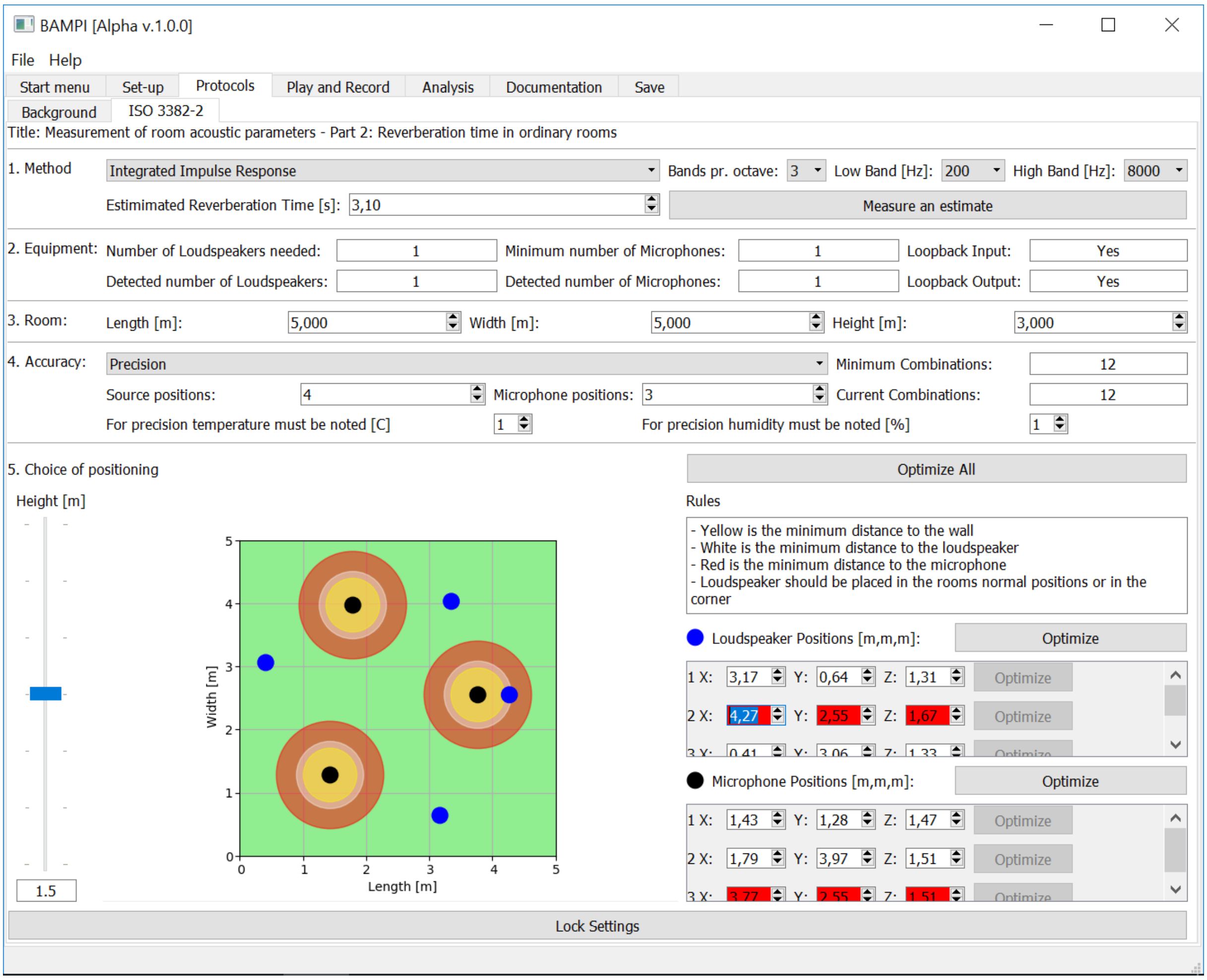


Figure B.7: Protocol menu in BAMPI.

The menu covers all essential settings which needs attention for an ISO 3382-2 measurement. The protocol is divided into five sections taking the user through all required steps:

1. Method Covers which method the user want to use, either using interrupted noise method or integrated impulse method. The desired resolution on fractional octave bands is selected along with the frequency range of interest. An estimated reverberation time is required as the program uses this time as an averaging constant when calculating interrupted noise decay curves or integration limits when calculating Schroeder decay curves. If the user is in doubt of the reverberation time and estimate function can be used which performs a simple reverberation time measurement.

2. Equipment A check will be performed to ensure all needed equipment is connected to the sound card. It checks for the required loudspeaker and microphones. If the impulse response is to be obtained it will check if a reference/loopback has been set.

3. Room The dimensions of the room which is to be measured is also needed, this is both for aid in placement and for documentation.

4. Accuracy The measurement accuracy can be divided into three classes of accuracy, namely survey, engineering and precision. The overall demand for each being defined by the amount of source-microphone positions. Survey having only 2 combinations, engineering with 6 or the most demanding, precision which requires 12 combinations. The precision method states that the 12 combinations are needed with at least 2 source positions and 3 microphone positions. Depending on the equipment input in the peripheral menu, the requirement will be displayed in the boxes. If a precision method measurement is to be followed, both temperature and humidity must also be measured.

5. Choice of positioning The most demanding part of the procedure is to determine where the source and microphone is to be positioned. Microphones should be placed at least a half wavelength apart and a quarter wavelength from the nearest reflective surface. The distance d_{min} between any source and microphone is to uphold eq. B.1.

$$d_{min} 2 \cdot \sqrt{\frac{V}{c \cdot \hat{T}}} \tag{B.1}$$

where V is the volume in cubic meters, c is the speed of sound and $\hat{T}$ is an estimated reverberation time.

B.6 | Stimuli Menu

The BAMPI system allows for multichannel recordings and playback. Each channel can be supplied with an individual stimuli of the users choosing. The stimuli/channel selection overview can be seen on figure B.8.

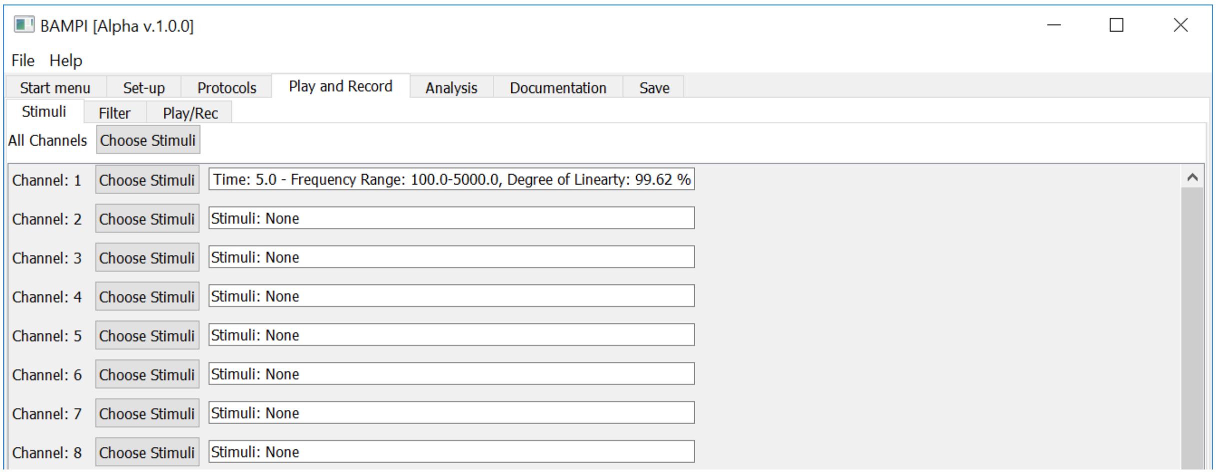


Figure B.8: Stimuli menu in BAMPI.

The option for providing a custom stimuli is available, allowing for premade stimulis to be used. The stimuli is automatically checked for amount of channels in the file and if the samplerate is identical. Should a generic test signal be desired it can be provided in the same menu. The menu for selecting a stimuli is shown on figure B.9. The program allows for selection of the following stimuli:

- White or pink noise
- Single frequency sinusoidal
- Both linear and logarithmic swept sines

Special care has been provided for the logarithmic sweep generator, synthesizing the entire signal in frequency ensuring high suppression of onset artifacts present in time domain synthesizing [Müller and Massarani, 2001]. An example of synthesized sweep can be seen in the acceptance test in appendix F under subsection F.1.4.

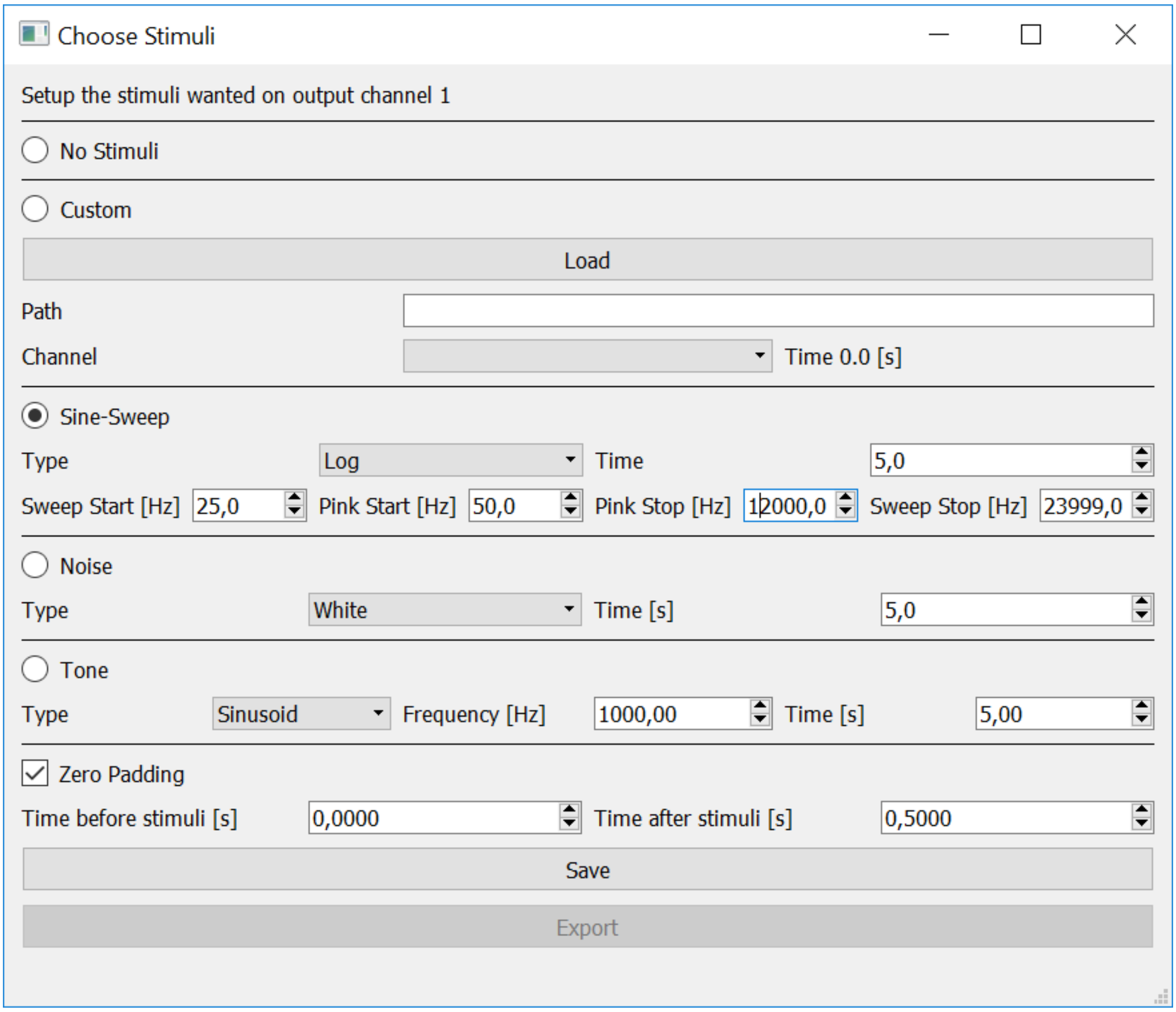


Figure B.9: Stimuli creation menu in BAMPI.

B.7 | Filter Menu

For each input and output channel it is possible to select a variety of filters for post processing of the signal. Both an unfiltered and processed version of each recording is saved within the program and it is possible to save both signal. The application for filter use ranges from suppression of pre amp noise to equalization of instrumentation. The selection of filters for each channel can be seen on figure B.10.

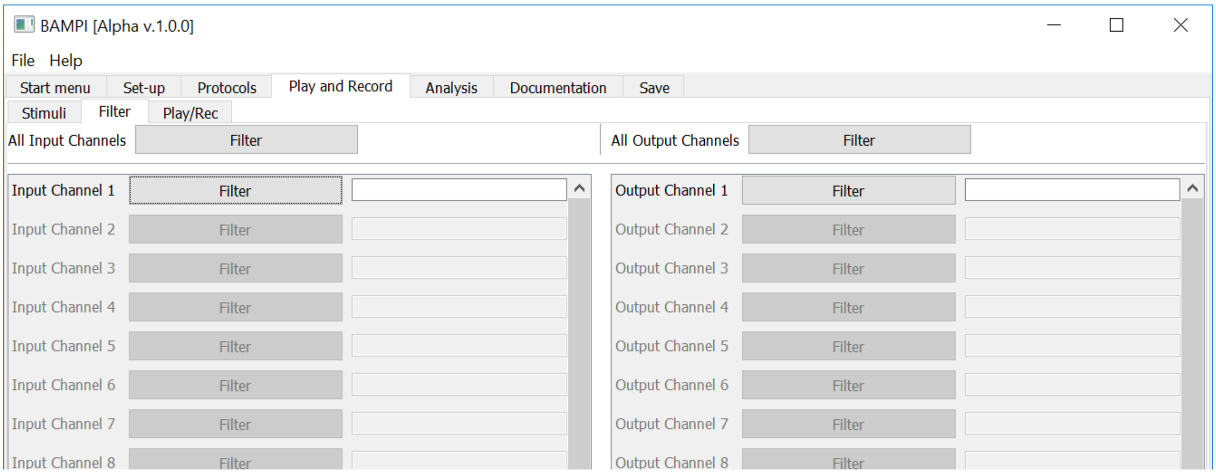


Figure B.10: Filter menu in BAMPI.

On figure B.11 the filter menu is shown. In the filter menu it is possible to design the required filter. The filter creation is handled internally by the user selecting the desired requirements for the filter and the system design a suitable filter.

The user must define the stop and pass band along with the desired attenuation in those bands for the filters to be designed. The option for applying IEC 61672 compliant A,B and C weighting curves have been made as well [IEC 61672-1, 2014]. Generic FIR and IIR highpass and lowpass filters are available. The order and topology of the filters is determined by the users in the combo-boxes.

A graphical equalizer is available to correct the frequency response of the equipment. The equalizer is defined in $\frac{1}{3}$ and $\frac{1}{1}$-fractional octave bands as this suits the majority of microphone manufactures correction curve measurements. Should a more complex filter be need, the option for loading specific filter coefficients generated in MATLAB or Python is available as well.

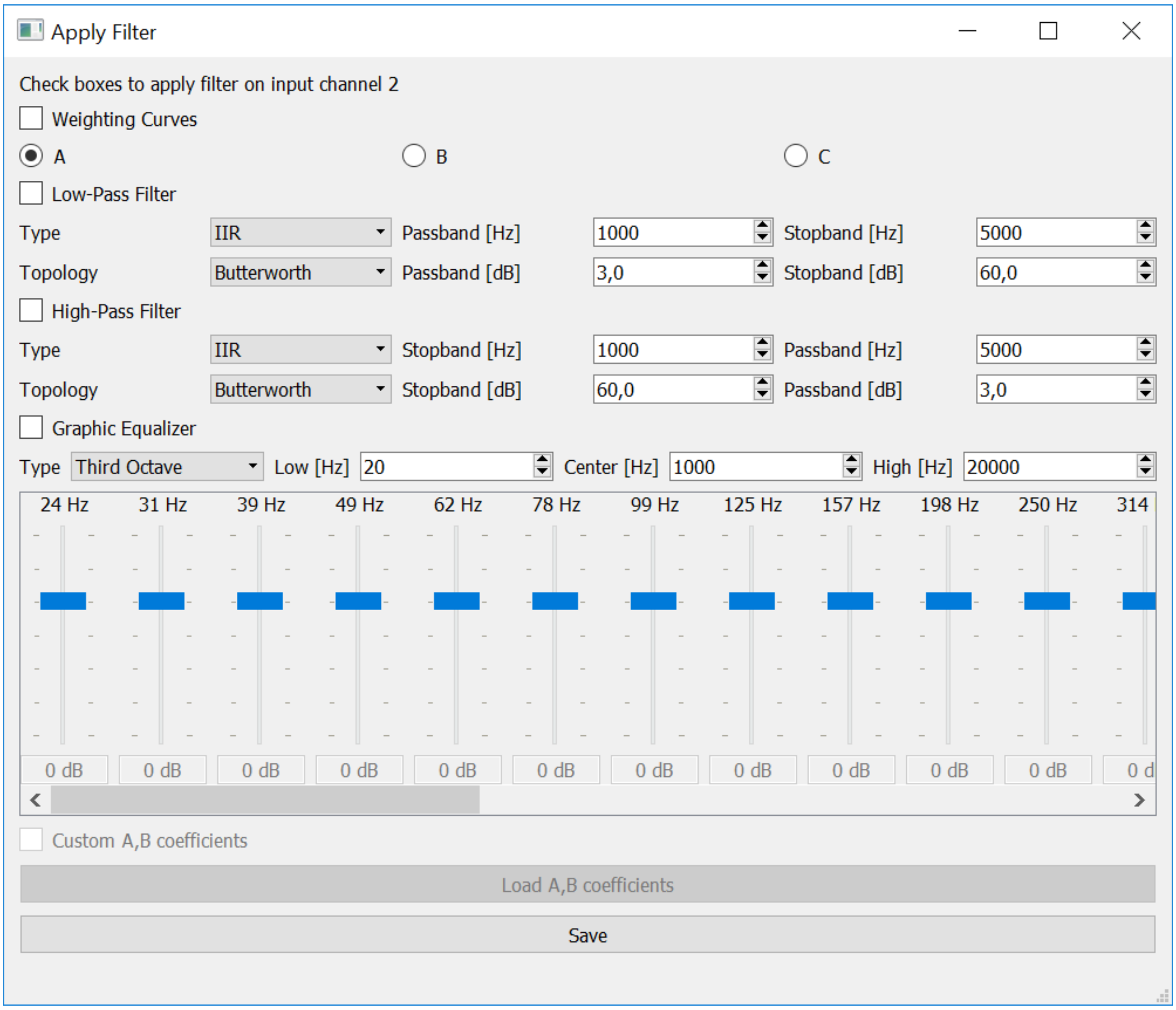


Figure B.11: Filter creation menu in BAMPI

B.8 | Play and Record Menu

The play and record function in BAMPI is designed with focus on multi channel recording. The menu for play an record can be seen on figure B.12.

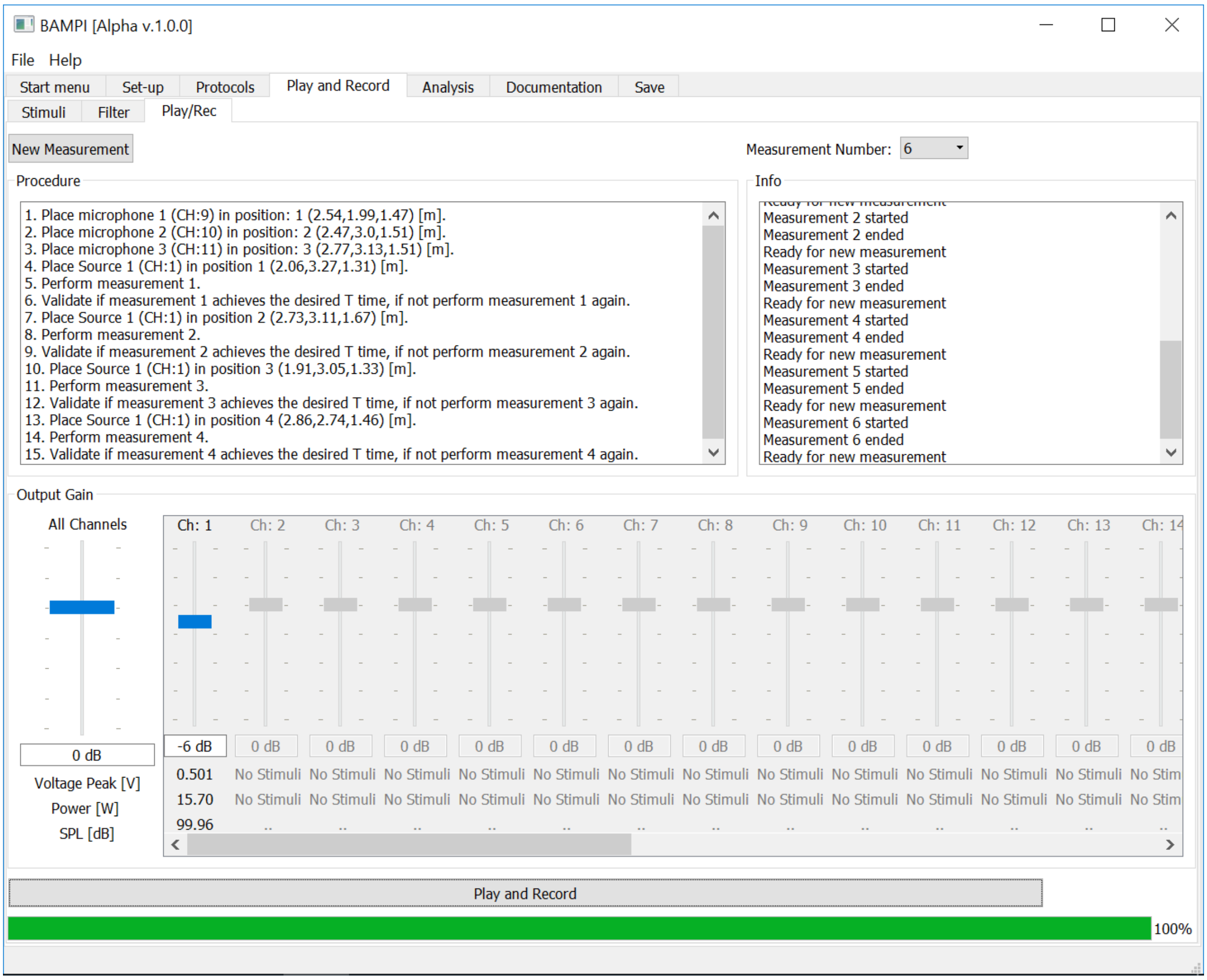


Figure B.12: Play and Record menu in BAMPI.

The menu is designed such each channel can have their gain individually adjusted. Following that the equipment has been noted with the correct specification, three estimation values will be shown. The voltage at the output of the sound card, the power needed on average for the given channel, taking into account; the gain of the amplifier(s), impedance and sensitivity of the loudspeaker. Based on the sensitivity an estimation of the sound pressure level at 1 meters distance is also provided. Should the voltage increase above IEC 60268-11 recommendations a warning will be given, minimizing the chance of none competent people breaking equipment [IEC 60268-11, 1987].

If a protocol is being followed, a set of instruction is provided for a correct procedure within that given protocol. Between each measurement an information box will provide notice if any problems occur during measurement that needs to be check in the analysis tab.

B.9 | Time Analysis Menu

Proceeding the recordings it is possible to perform a certain amount of analysis in the time domain. The menu for time domain analysis is shown in figure B.13.

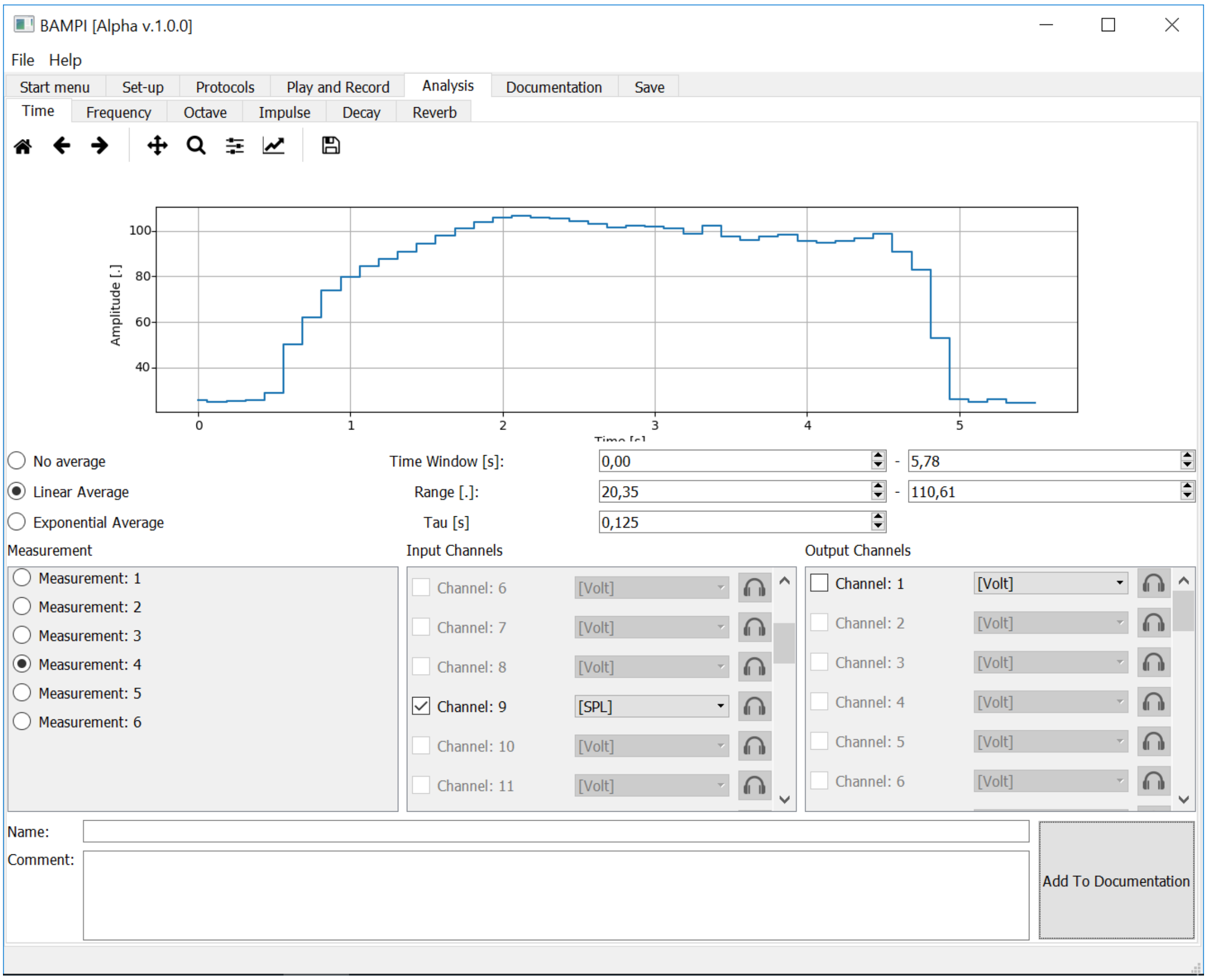


Figure B.13: Time analysis menu in BAMPI.

Within the time analysis it is possible to evaluate the raw signal or as an average signal, both linear and exponentially averaged with a user defined integration time. The signal can be shown in either dBv, dB SPL, Voltage, Pascal or the internal number value determined by the sound card. It is possible to evaluate multiple channels within the same measurement.

Should an abnormality be present that is desired to document, it is possible to add these informations to the documentation that is developed during the saving procedure.

B.10 | Frequency Analysis Menu

If the spectral content of the recorded signal is desired to be seen, this is also possible. With the frequency domain analysis tool, shown in figure B.14, it is possible to see the recorded signal using an N-point Fast Fourier Transform.

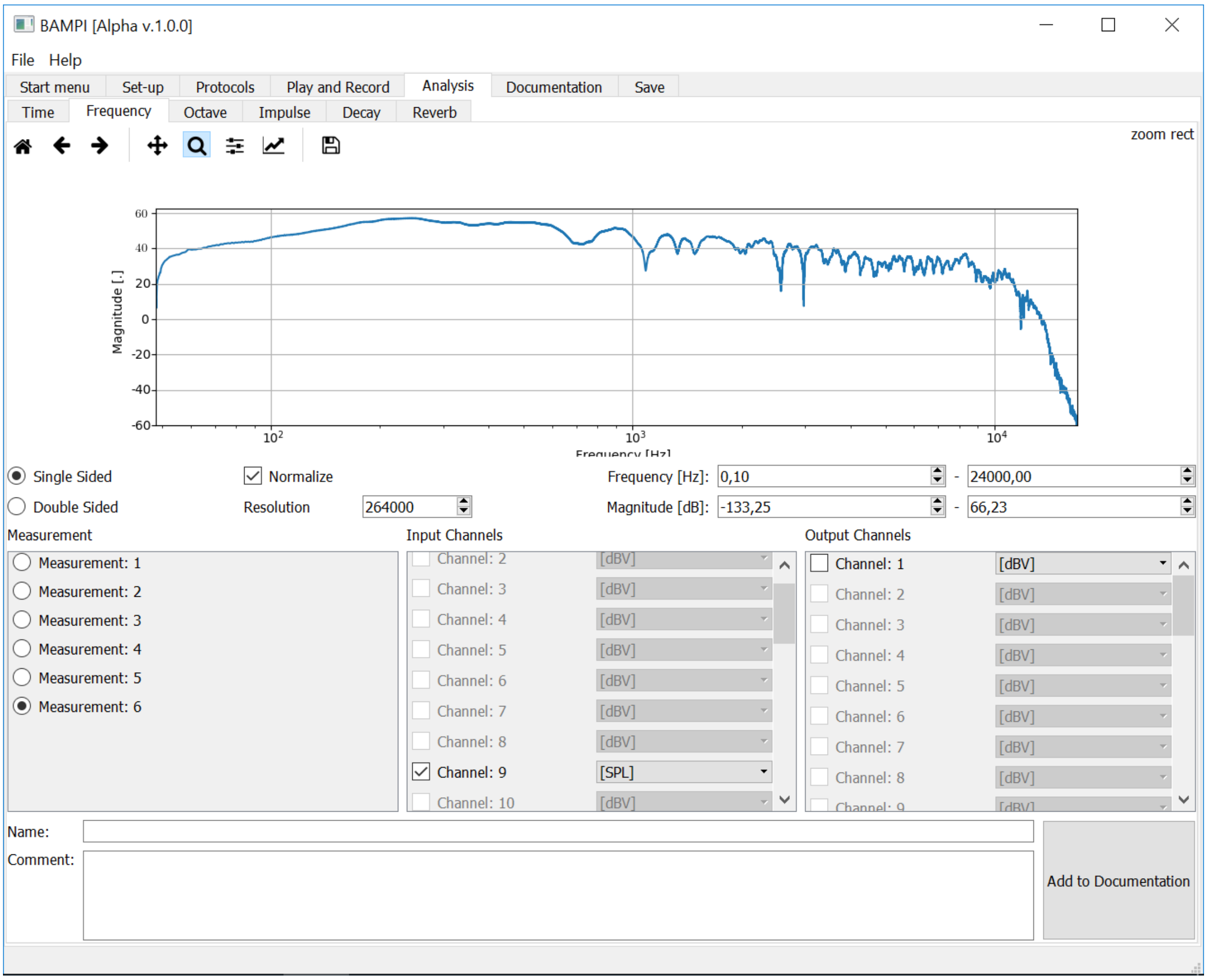


Figure B.14: Frequency analysis menu in BAMPI.

The signal can be shown both single and double sided. If the single sided spectrum is shown it will automatically add the remaining power from the mirrored spectrum to the response[Yu, 2014].

B.11 | Octave Analysis Menu

If a spectrum analysis in fractional octave bands is desired this can be achieved. The program allows for factional octave bands in the following predefined settings; $\frac{1}{1}, \frac{1}{3}, \frac{1}{6}, \frac{1}{12}, \frac{1}{24}, \frac{1}{48}$. The octave analysis menu can be seen on figure B.15.

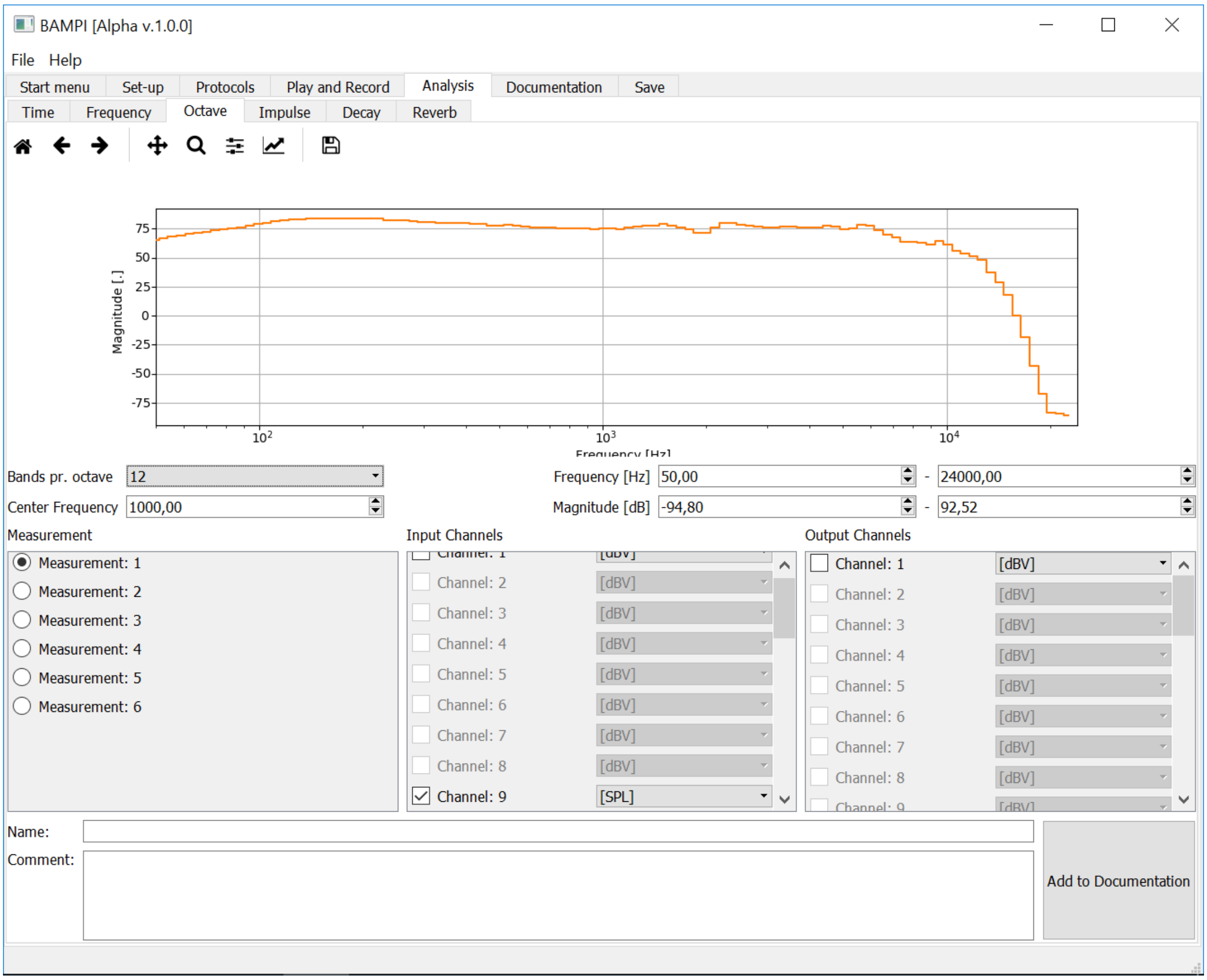


Figure B.15: Octave analysis menu in BAMPI.

The octave menu uses the settings shown on the menu and generates a IEC 61260-1 class 0 compliant filter bank [IEC 61260-1, 2014]. The filters are applied using zero-phase filtering [Oppenheim and Schafer, 2009]. By use of zero phase filtering the phase will remain unchanged and only the magnitude of the signal will be affected by the filtering.

B.12 | Impulse Analysis Menu

The program allows for analysis of calculated impulses if a loopback/reference signal is provided. The Impulses analysis menu can be seen on figure B.16.

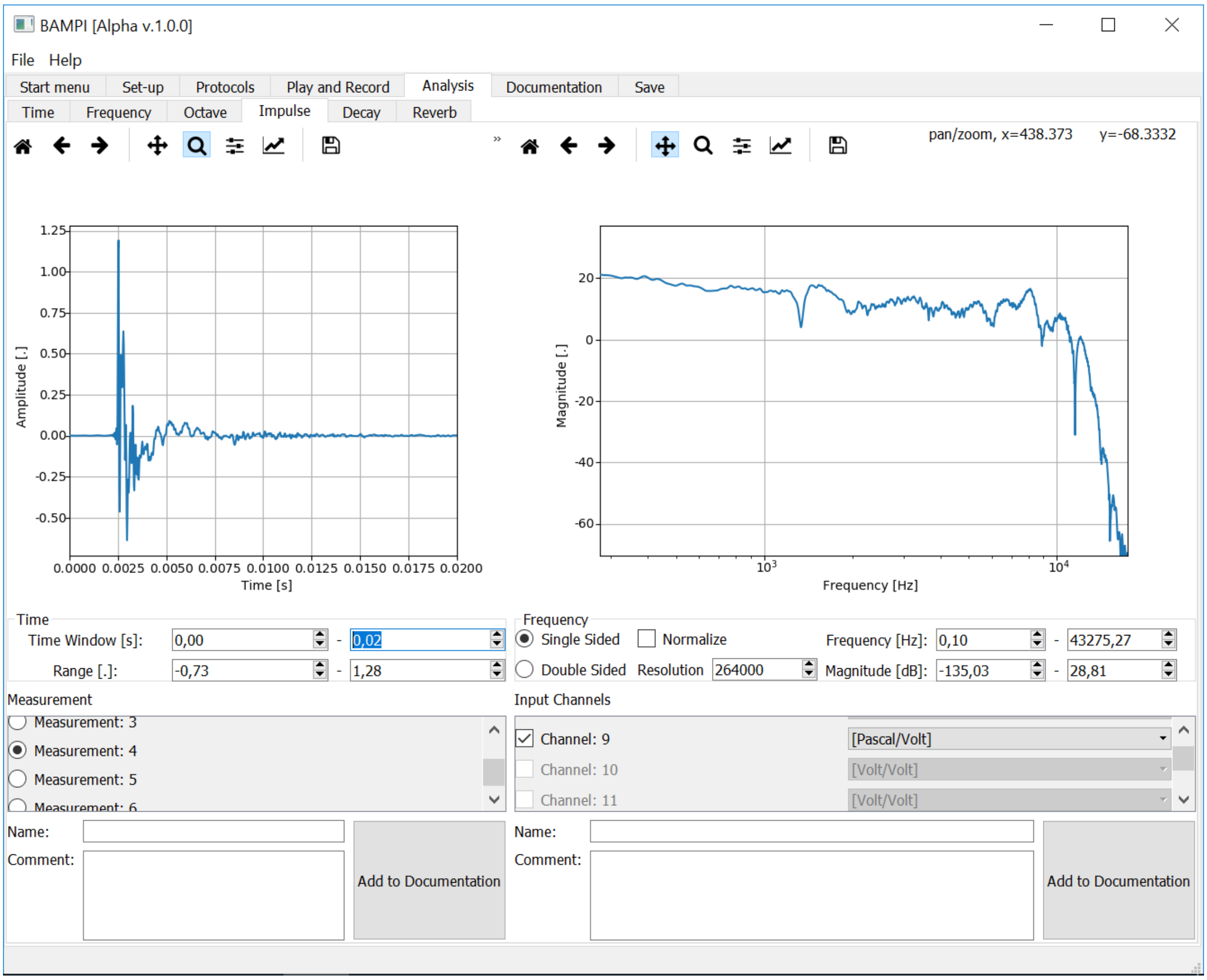


Figure B.16: Impulse analysis menu in BAMPI.

The impulse analysis tool allows for visualization of the impulse in both time and frequency and allows for the same adjustments as in the time and frequency menu. The calculation of the impulse is explained in subsection B.12.1.

B.12.1 Impulse Extraction

For extraction of the impulses response from the measured signal a linear deconvolution is done. The flow of such a procedure is depicted in figure B.17. As a convolution is circular by definition a zero padding to double length is done to make sure the impulse does not wrap around. The signals are then subjected to a spectral bin-by-bin division before it is inverse Fourier transformed back to time, yielding the impulse response. The linear deconvolution also yields the harmonic distortion in negative time, i.e. the tail of the impulse, these are however of no interest and discarded [Müller and Massarani, 2001].

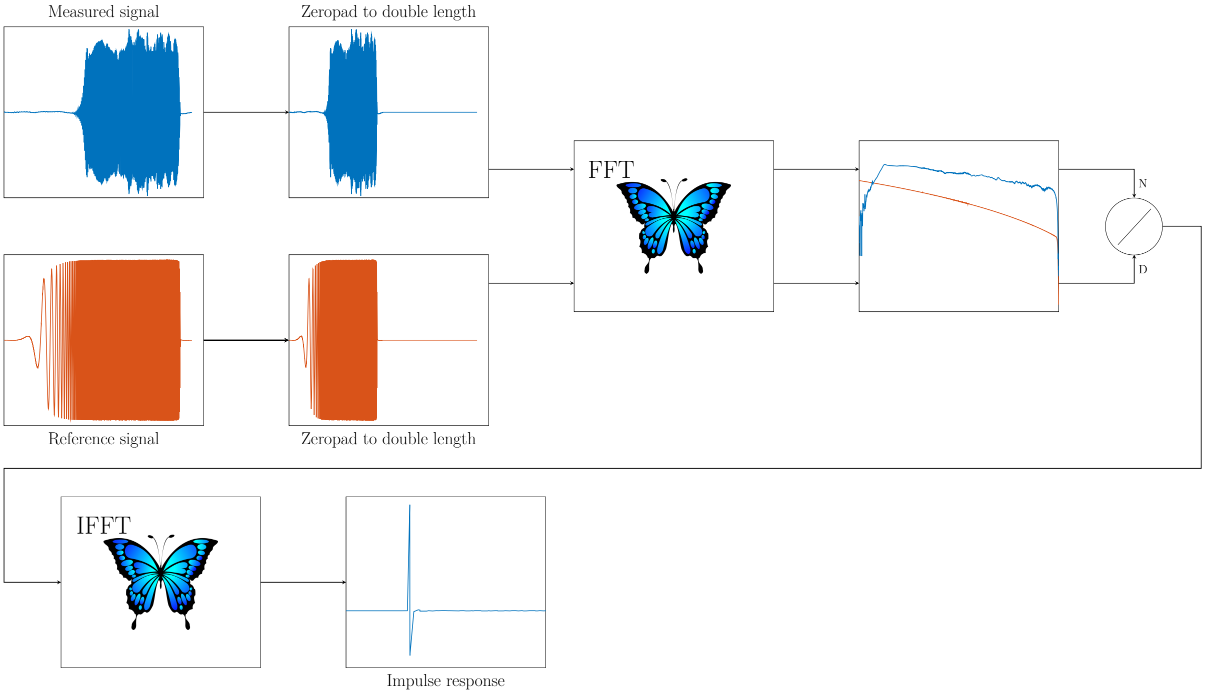


Figure B.17: Flow for calculating the impulse response by linear deconvolution using spectral division as presented by [Müller and Massarani, 2001]. Distortion products in negative time is not shown.

B.13 | Decay Curve Analysis Menu

In the case of an ISO 3382-2 measurement being performed it is possible to analyze each individual octave band and manual evaluate the decay curves. The menu for the decay curve analysis tool is shown on figure B.18.

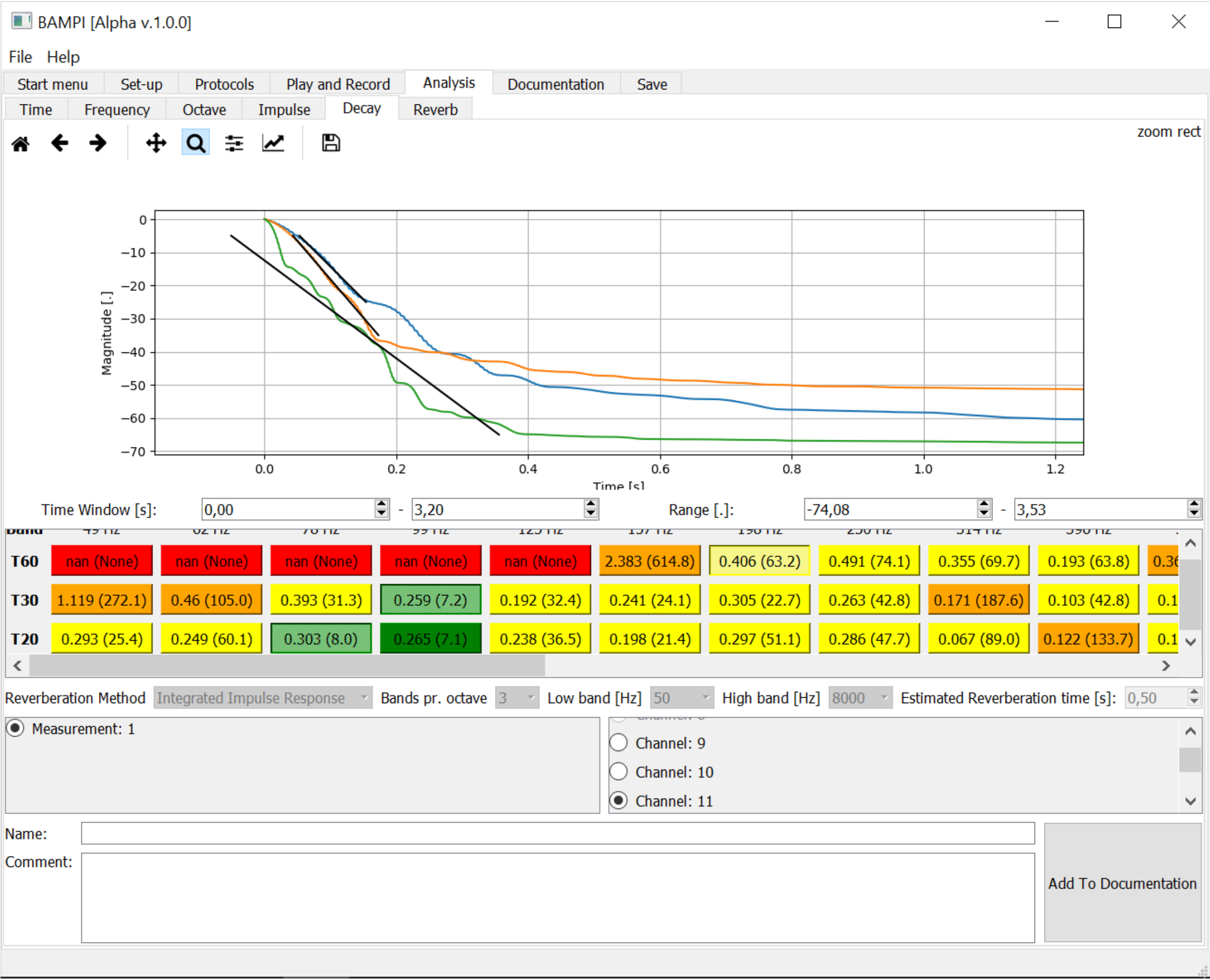


Figure B.18: Impulse analysis menu in BAMPI.

Each decay curve is evaluated as described in subsection B.13.1, conforming with ISO 3382-2. Each colored box in the menu describes a decay curve status. Four colors can be displayed:

- A green box denotes a decay curve fit below 10 ‰
- A yellow box denotes a decay curve fit below 100 ‰
- A orange box denotes a decay curve fit above 100 ‰
- A red box denotes a decay curve which did not reach the required signal-to-noise ratio

B.13.1 Calculating and evaluating decay curve

When the impulse response is calculated from the deconvolution process it is possible to determine the decay curves using the Schröder backward integration, shown in eq. B.2 [Schroeder, 1965].

$$E(t) = \int_t^\infty p^2(\tau)d\tau = \int_\infty^t p^2(\tau)d(-\tau) \tag{B.2}$$

or for a discrete signal

$$E(t) = \sum_{\tau=t}^{\tau=\infty} p^2(\tau) = \sum_{\tau=\infty}^{\tau=t} p^2(\tau) \tag{B.3}$$

As stated in section A.1 all T-values are evaluated from -5 dB below steady state. From these points linear regression is performed until the curve has decayed either 60, 30 or 20 dB. Using the regression line the reverberation time is evaluated. An example of a decay curve extracted from a room impulse can be seen on figure B.19. If the entire impulse is integrated it will allow for a large amount noise to be integrated reducing the linearity of the decay curve, the effect is slightly seen on figure B.19 where the build-up of noise affect the linearity of the decay. To avoid a to large effect, the estimated reverberation time specified in the protocol tab is used as integration limits. By trial and error it was selected to set the limit of integration for low frequencies (< 200 Hz) to five times the estimated value and 3 times for higher frequencies.

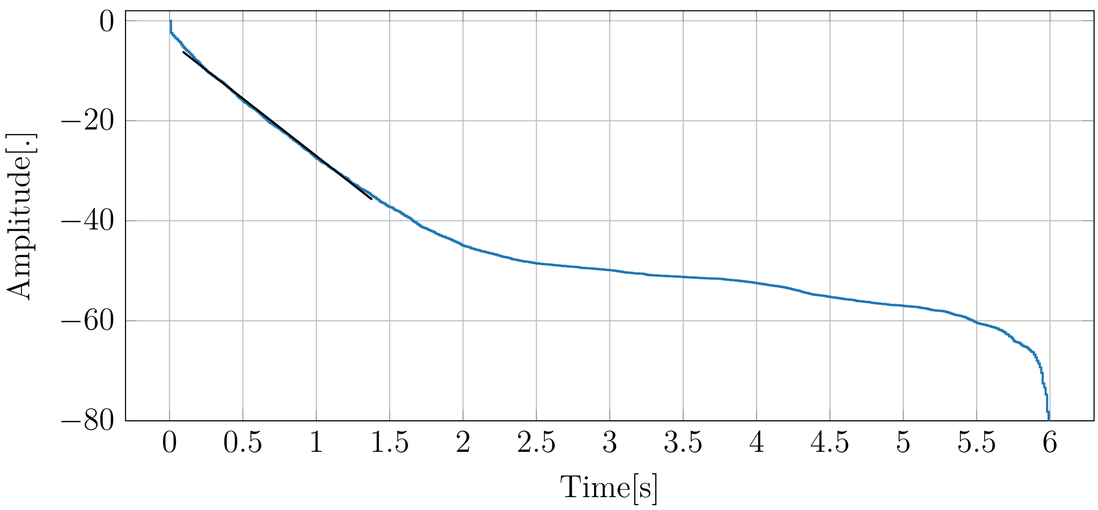


Figure B.19: Example of a decay curve derived from the impulse response of The Lady Chapel, St Albans Cathedral in England[Open Air Database, 2010] Decay curve (●) and T30 regression line (●).

To determine whether the decay curve is sufficiently linear, the regression curve determined should be between 0 to 5 ‰. Values higher than 10 ‰ is indicating a decay curve which is far from linear and maybe affected by modes and may be suspicious [ISO 3382-2, 2008]. To determine the degree of linearity eq. B.4 is used, for reference the linearity of the T30 regression line plotted on figure B.19 is 2 ‰.

$$\zeta = 1000 \cdot (1 - r^2) \tag{B.4}$$

Where ζ is the degree of linearity in ‰ and r^2 is determined using eq. B.5.

$$r^2 = \frac{\sum_{i=1}^{n}(\hat{L}_i - \bar{L})^2}{\sum_{i=1}^{n}(L_i - \bar{L})^2} \tag{B.5}$$

Where L_i is the level on the decay curve in decibels and $\hat{L}_i$ is the estimated value of sample number i on the linear regression curve. The mean value of the samples L_i is furthermore determined using equation eq. B.6.

$$\bar{L} = \frac{1}{n}\sum_{i=1}^{n} L_i \tag{B.6}$$

When all reverberation values, T_{20},T_{30},T_{60} have been calculated, a mean value from each fractional octave band is determined. The program automatically selects the best values based on the following criteria:

1. The band which contains the most calculated values, i.e. all 12 values in T_{20} instead of 10 in T_{30}.
2. If two mean values differ more than 5 %, the "easiest" value to achieve is chosen, i.e. T_{20} over T_{30}.
3. The "hardest" reverberation value to achieve i.e. if a band has 12 values in all three parameters, the T_{60} is chosen.

B.14 | Documentation Menu

The program allows for complete documentation of the procedure, by allowing the user to insert information about the procedure which will be formated into a measurement report compiled in LaTeX. The first menu for documentation is shown on figure B.20 which denotes all the general information.

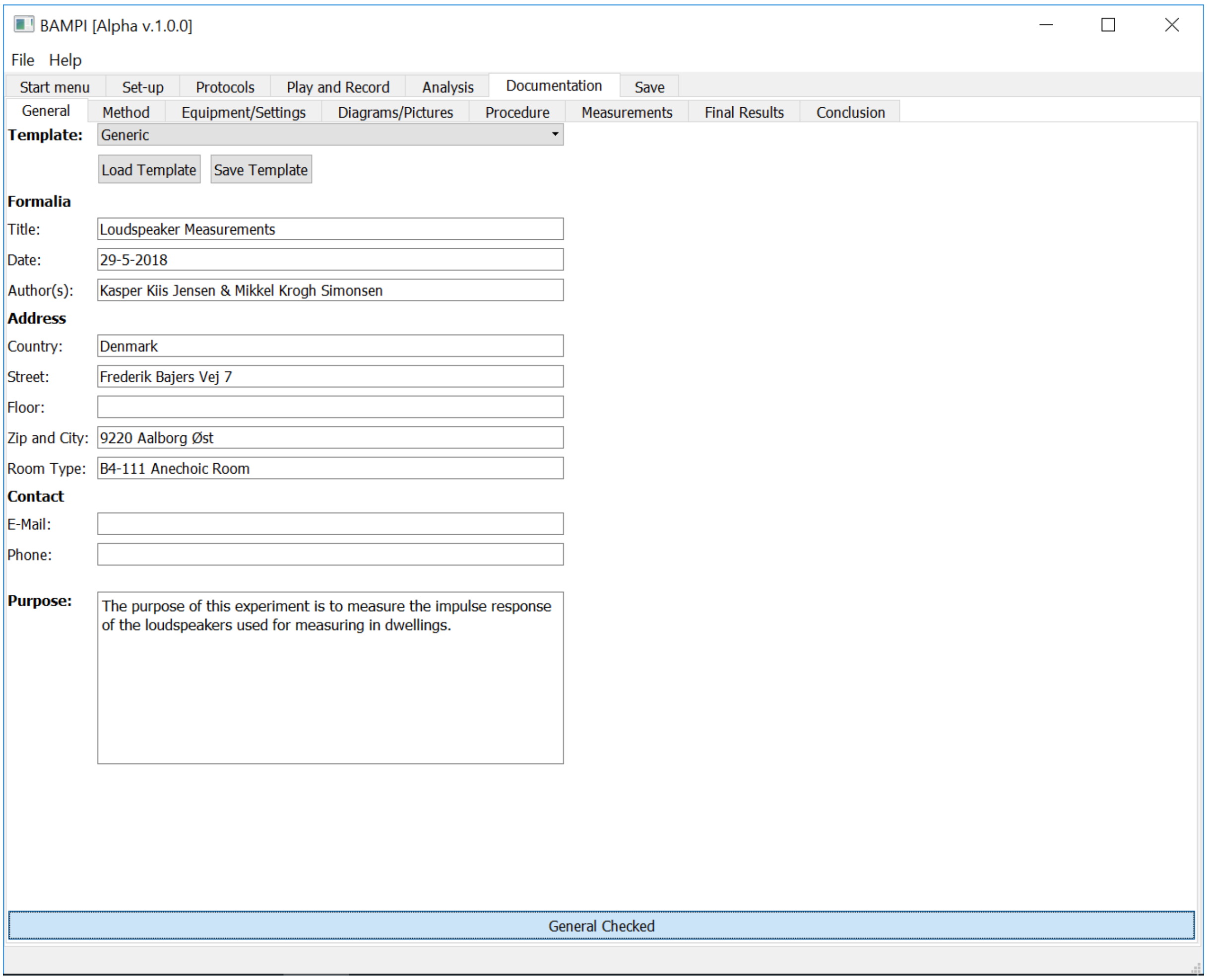


Figure B.20: General Documentation menu in BAMPI.

In case this is a measurement session which is going to be repeated multiple times, it is possible to load a pre-made documentation file. This file provides all known information like authors, additional information, procedures etc. If a protocol has been selected it will automatically choose a documentation template of that type e.g. should a ISO 3382-2 protocol have been followed it will document all microphone and speaker positions etc.

B.15 | Method Documentation Menu

If different methods throughout the measurement have been used which is not documented in the standard it is also possible to document them. The documentation menu for different methods are shown on figure B.21.

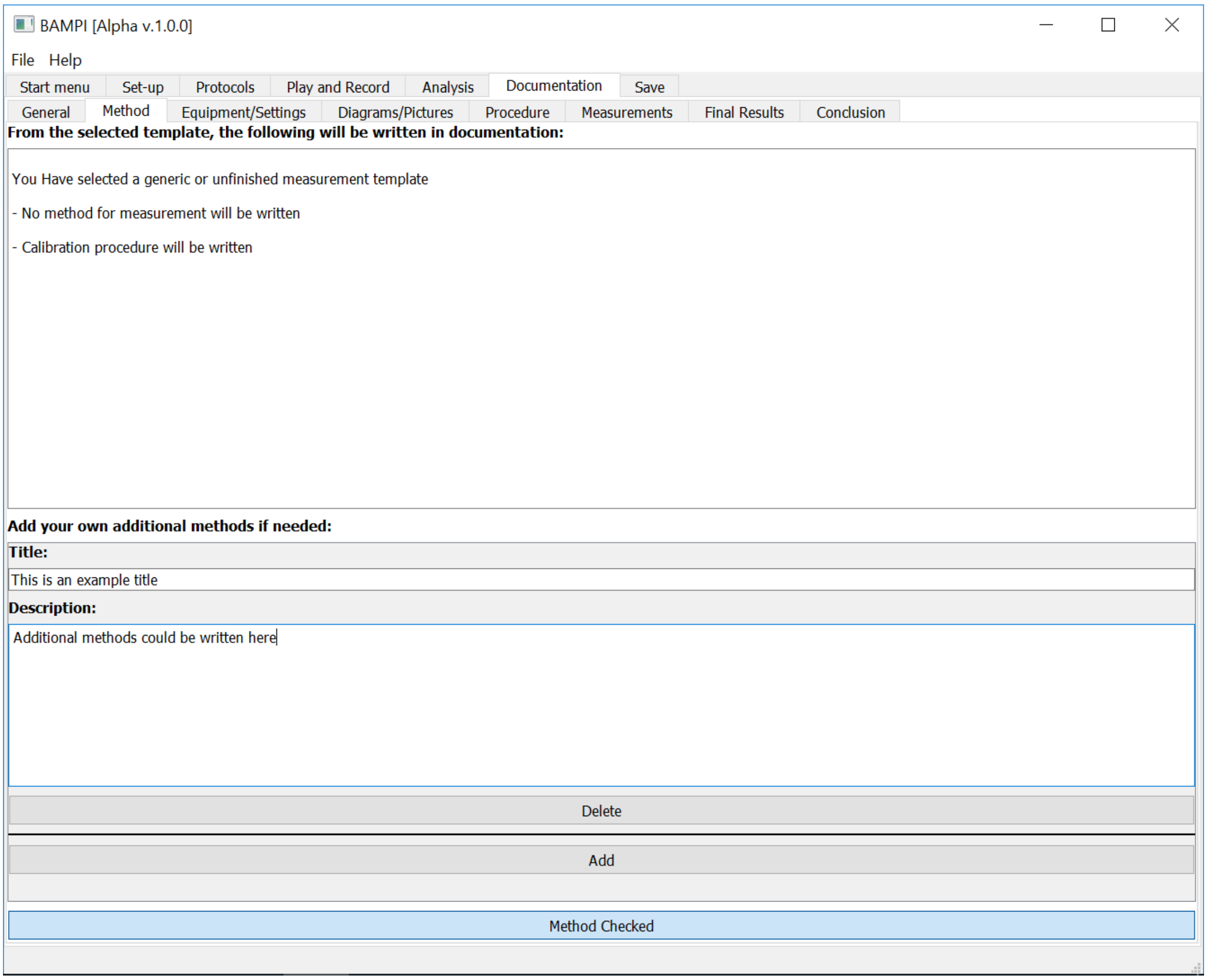


Figure B.21: Method Documentation menu in BAMPI.

Additional methods are protocols that is not implemented, specific microphone placement or special use of equipment like goose necks for microphones etc.

B.16 | Equipment Documentation Menu

The equipment documentation displays all already noted equipment and allows for adding additional items. Equipment noted in the peripherals menu is automatically documented and does not need any additional care. The equipment documentation menu allows for documentation of additional equipment which can not directly be seen in the measurement chain. The menu can be seen on figure B.22.

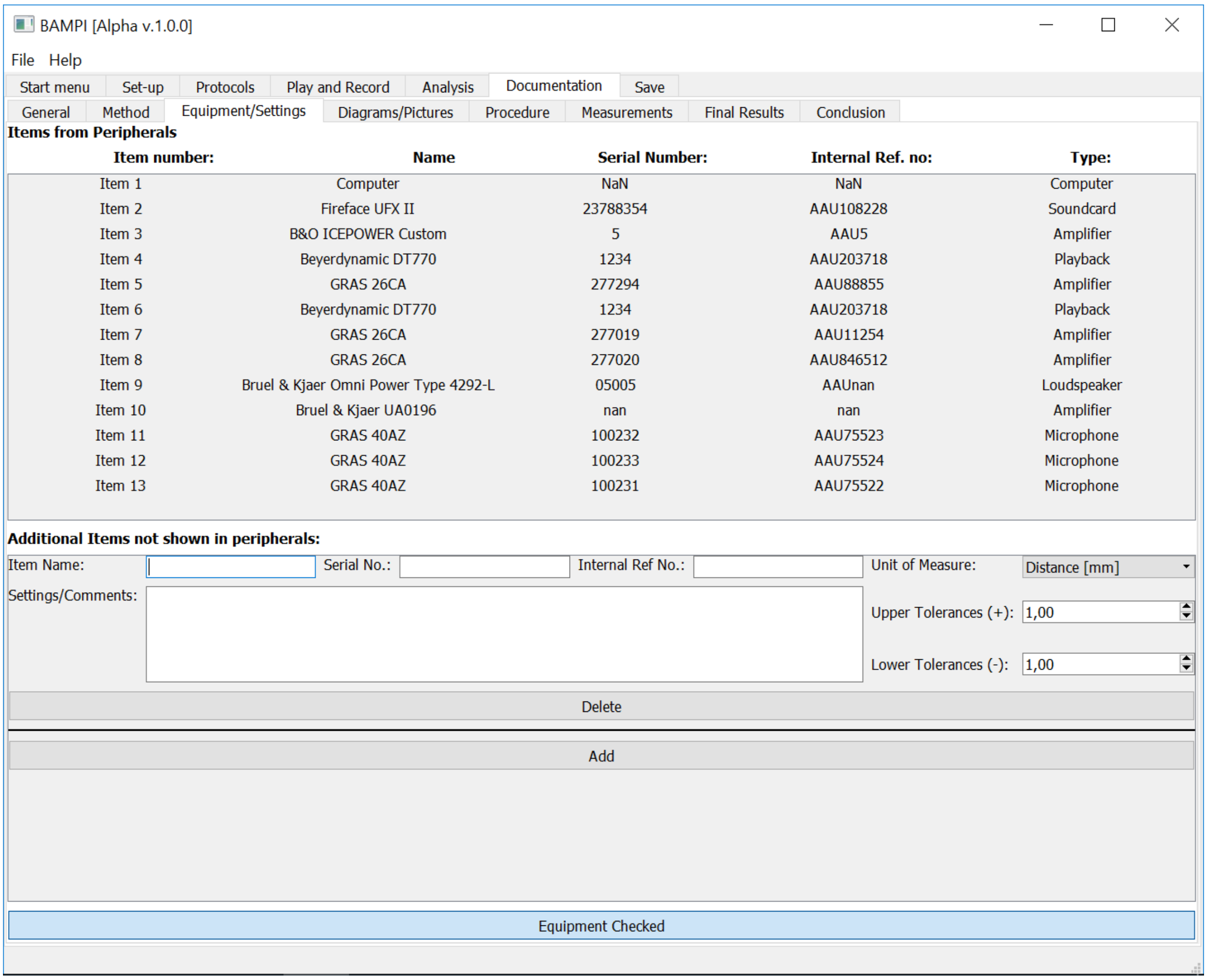


Figure B.22: Equipment Documentation menu in BAMPI.

The additional equipment is noted with all the same information as the equipment in peripherals with the exception that all additional equipment must be noted with a unit of measure, e.g. temperature, Pascal, meters etc.

B.17 | Diagrams and Picture Documentation Menu

The program allows for adding pictures into the documentation. The picture and diagrams menu can be seen on figure B.23.

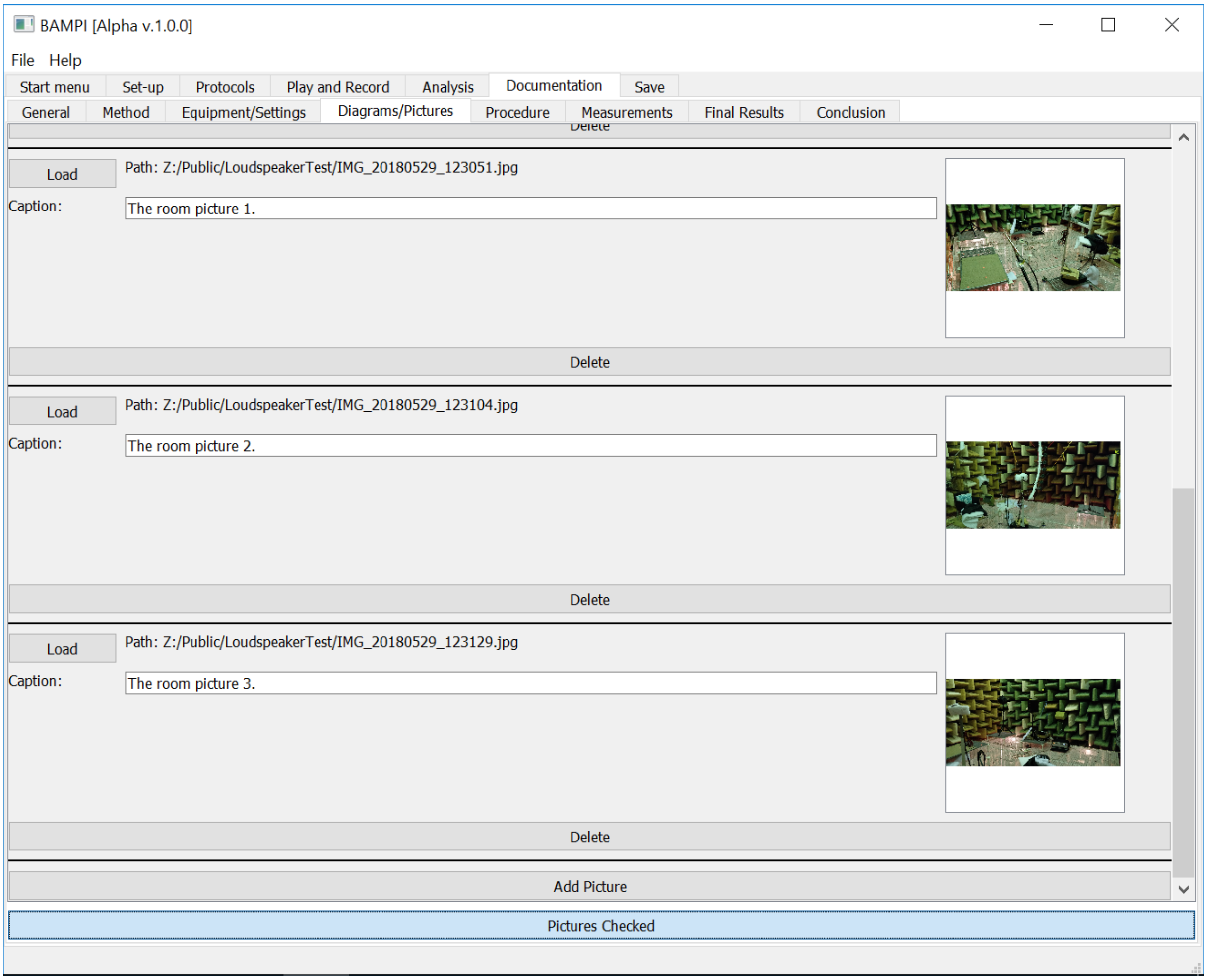


Figure B.23: Diagrams and Picture documentation menu in BAMPI.

All pictures which a loaded into the program are saved along with a descriptive caption. They are automatically stored together with all additional data in case of additional use.

B.18 | Procedure Documentation Menu

Support for additional procedure documentation, beyond what is automatically documented if a protocol is being followed is also available. The menu for procedure documentation can be seen on figure B.24.

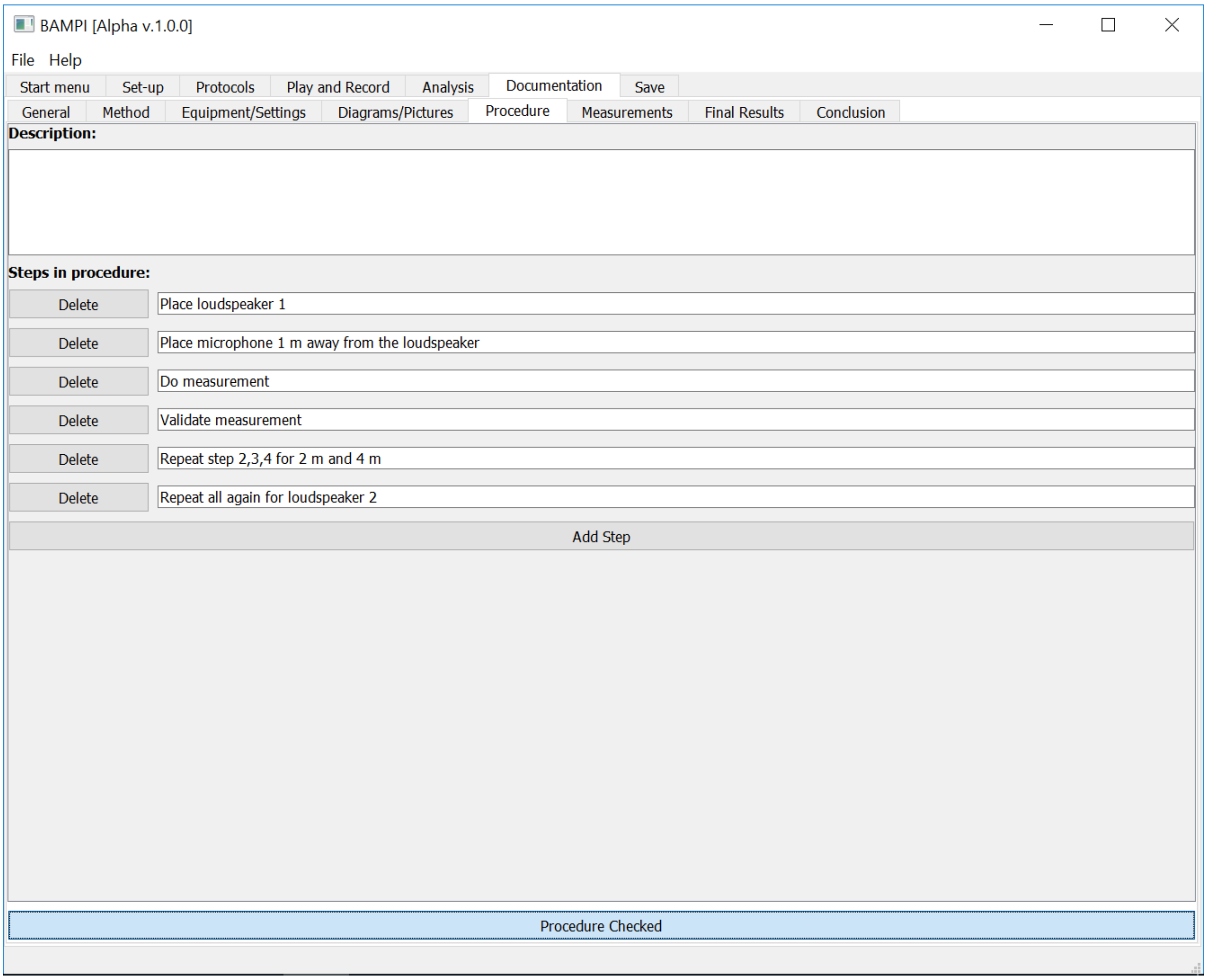


Figure B.24: Procedure documentation menu in BAMPI.

As stated previously, the BAMPI program will automatically write a protocol procedure if a specific protocol is selected. This procedure can be edited if something was not followed in the order stated or additional steps are to be added.

B.19 | Measurement Documentation Menu

All measurement done within the program is automatically documented in measurement documentation tab. The menu is shown on figure B.25.

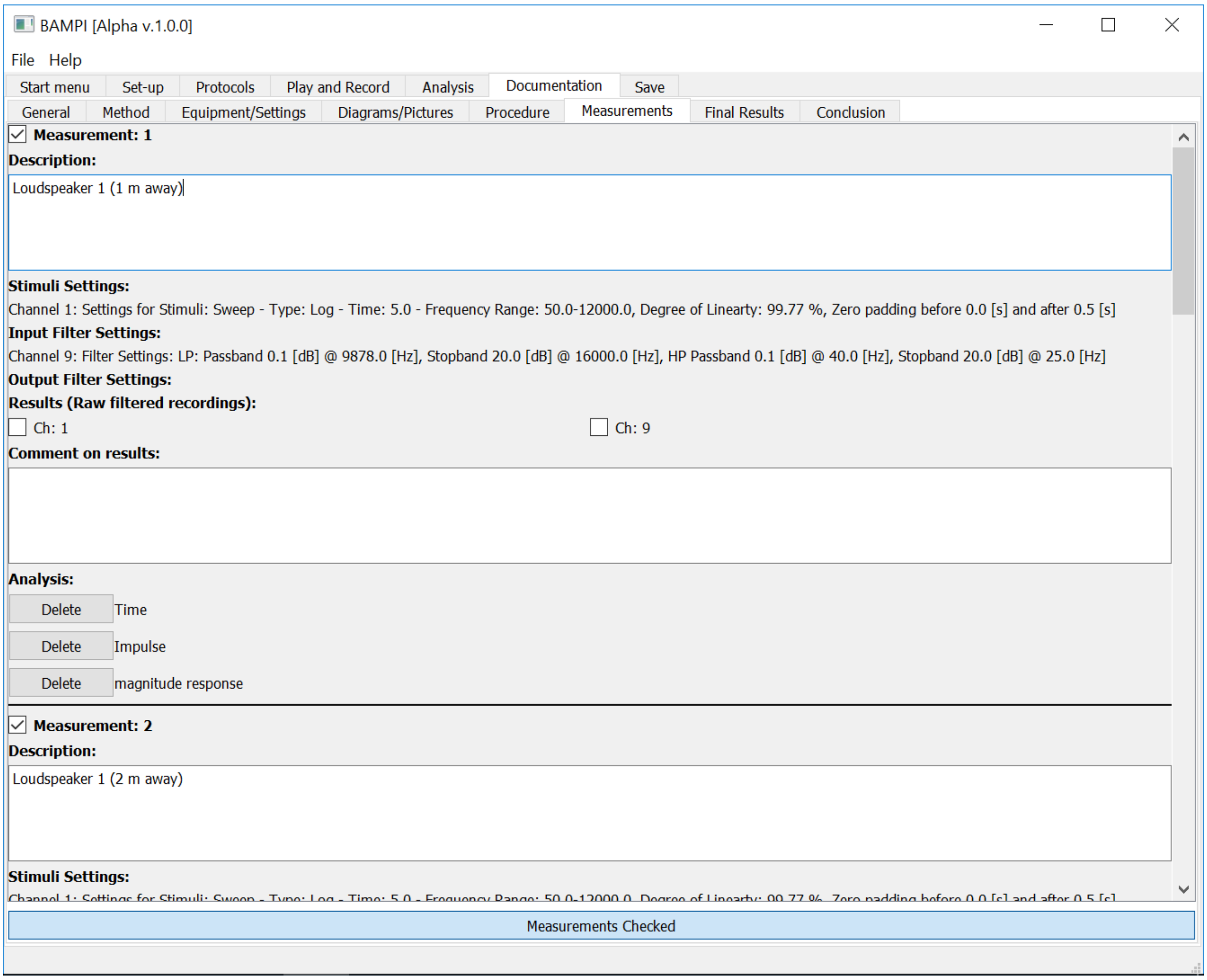


Figure B.25: Diagrams and Picture documentation menu in BAMPI.

When a measurement has been performed it will prepare for comment on the specific measurement along with a description of said measurement. Filter settings for both input and output is also showed. If any documentation have been added using the analysis tools it will also be displayed in this menu. If any of the documented analysis tool are to be deleted before everything is saved it will also be handled in the menu.

An option for displaying raw measured results are also provided in case this will provide essential understanding of the measurement, these are as default, to minimize complexity in the report, not selected.

B.20 | Conclusion Documentation Menu

The option of concluding on the measurement are also provided. figure B.26 shows the menu for adding any known errors and a conclusion.

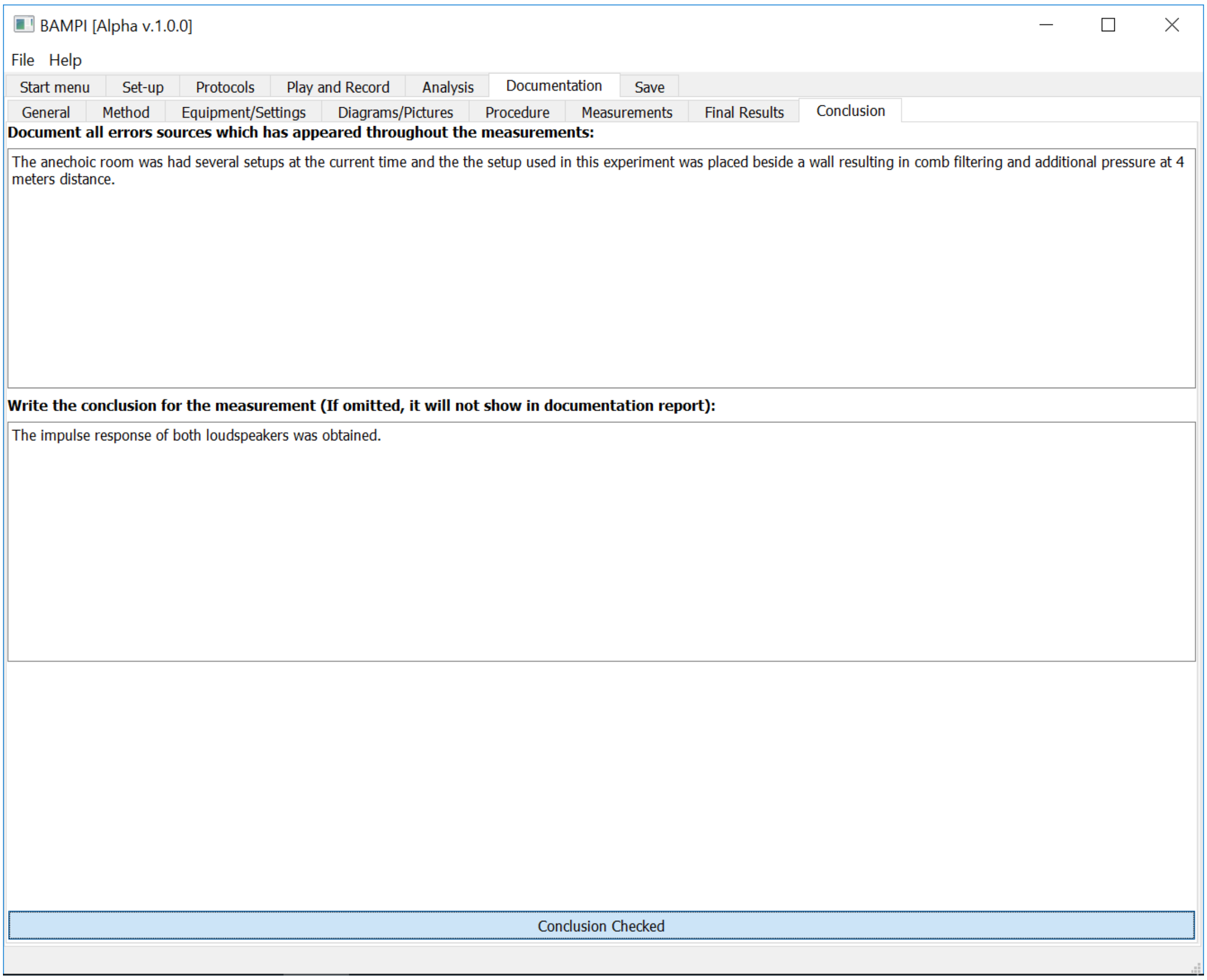


Figure B.26: Diagrams and Picture documentation menu in BAMPI.

If a conclusion is not added to the documentation it will automatically be left out in the documentation. Should there be no errors, and the field for noting errors left blank, it will be stated that no errors was noted.

B.21 | Save Menu

When all measurement have been made and the desired results have been achieved, the save tab will provide with the option of saving all information noted in the program. Figure B.27 shows the save menu.

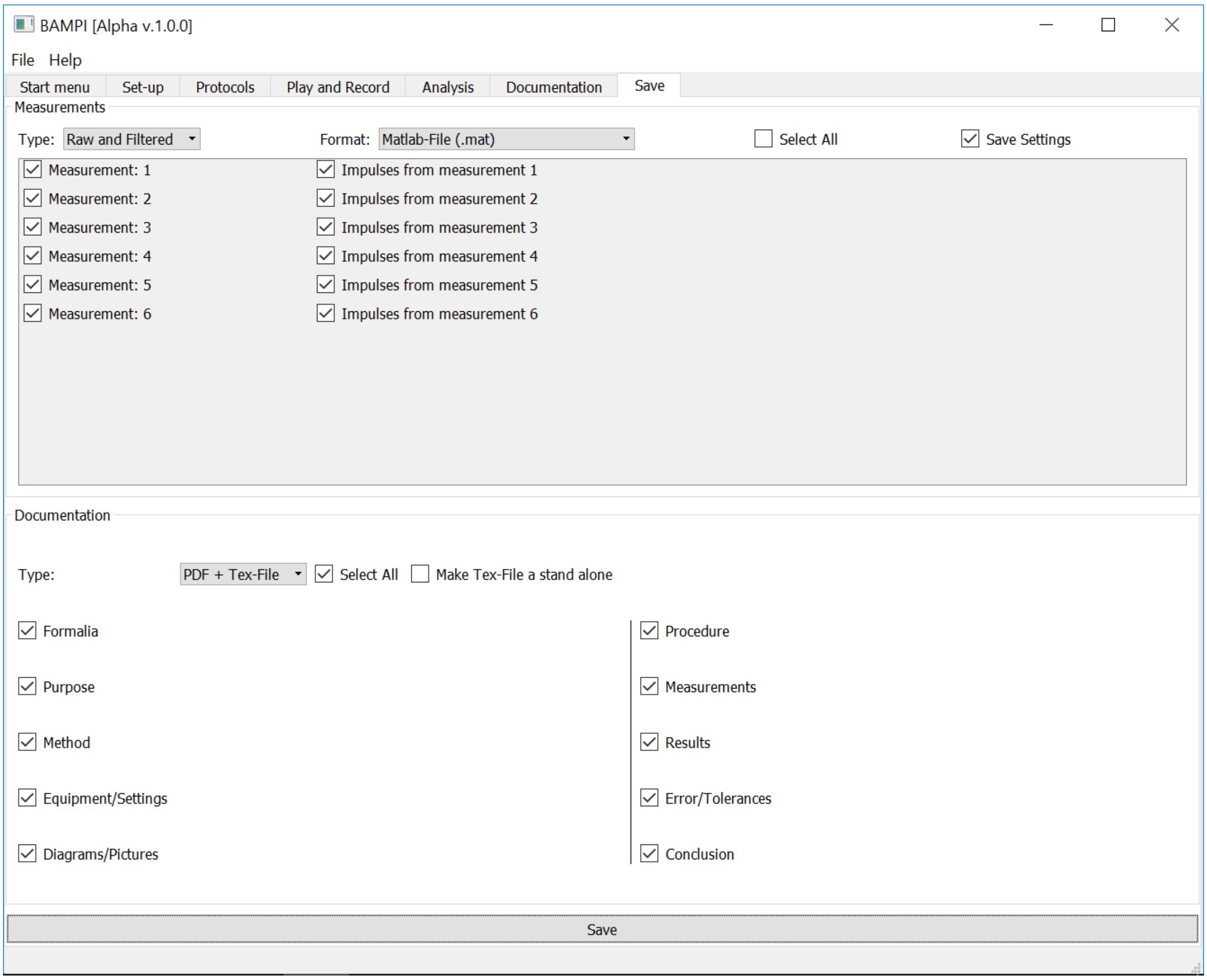


Figure B.27: Save menu in BAMPI

In the save menu it is possible to select what is desired to save. Either completely raw measurement, filtered or both along with their respective impulse response for each channel, if a loopback have been present.

The user is given the option of saving in different formats, both; .wav, .mat and .h5 covering both MATLAB, Python and Audio players.

The user is given the option of removing some documentation if this is not desired. As a default, the system saves a complete measurement report along with all settings and calibration values.

The report is saved as LaTeXfile and can be either saved with only the .pdf-file or with both .pdf- and .tex-files. The report can be saved as a standalone report as an insert for a larger report structure.

C | BAMPI Procedures

The purpose of this appendix is to describe the creation of a workspace, the creation of a report template and the measurement procedure when measuring according to ISO 3382-2. The source code can be found on the enclosed CD in the `SourceCode`-folder. No compiled executable exist at this point and a python environment is needed to run the program. The program can be started by executing `main.py` assuming all the required dependencies are installed.

C.1 | Creating Workspace and Template files

Creating a Calibrated Workspace

The following procedure describes the creation of a workspace which can be used for further measurements.

1. Start the BAMPI-program and select *New Measurement Session*.
2. The program detects all available sound devices and the user is to select the desired ASIO driven sound card connected from the displayed menu.
3. Navigate through the *Input* and *Output*-tab to select the needed input and output channels. An example for input selection can be seen on figure C.1.

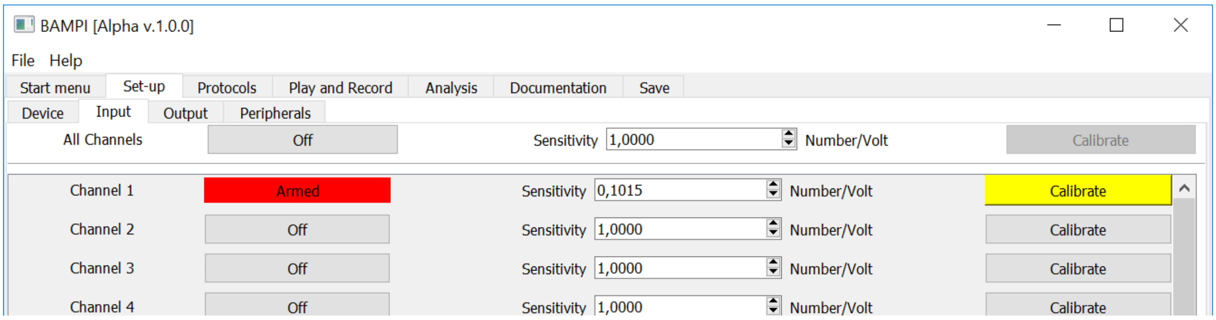
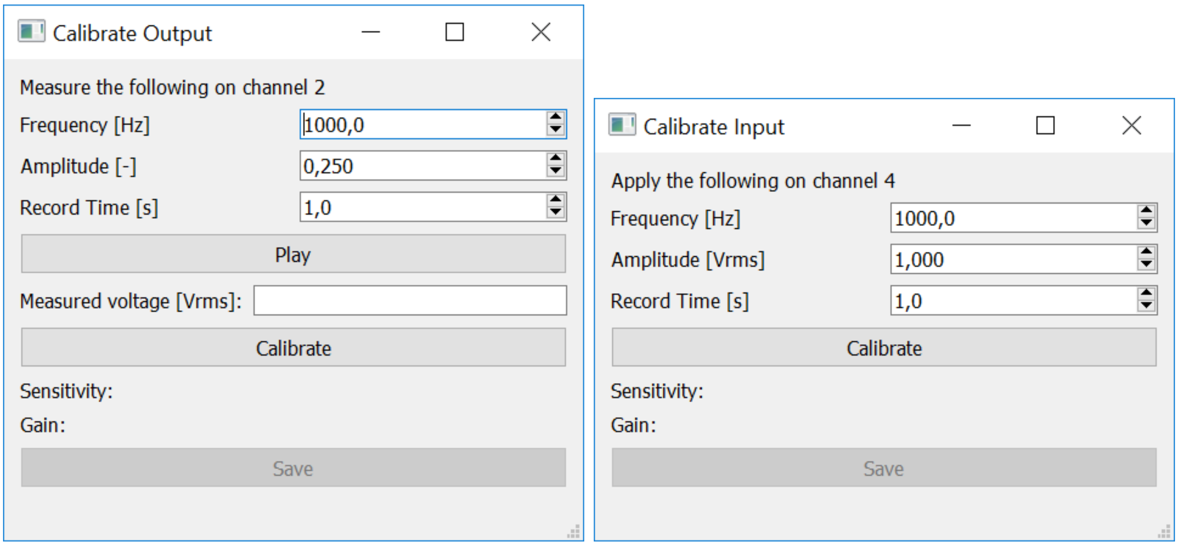


Figure C.1: Screenshot of the input selection menu.

4. Calibrate each selected input and output for the chosen sound card using the procedure stated on the screen. The calibration windows can be seen on figure C.2.
   (a) For all inputs a known sinusoidal signal is to be applied. The RMS voltage of the signal is noted in the program and the conversion ratio $\frac{Number}{Volt}$ is calculated.
   (b) For all outputs a known sinusoidal signal is to be measured. The RMS voltage of the signal is noted in the program and the conversion ratio $\frac{Volt}{Number}$ is calculated.

- A calibrated channel is denoted with a green button and a user/human altered and none calibrated button is denoted with a yellow button.



(a) Window for output calibration. **(b)** Window for input calibration.

Figure C.2: Screenshot of the input and output calibration windows.

5. Connect all needed peripheral devices into the sound card. All items are noted with respective gains, serial no, and other specifications. All informations noted are saved to documentation. The peripheral setup interface can be seen on figure C.3.

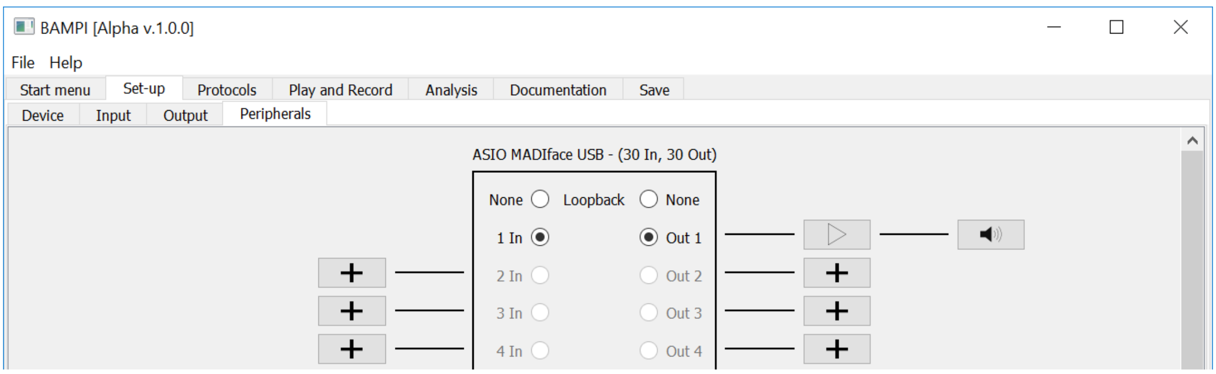
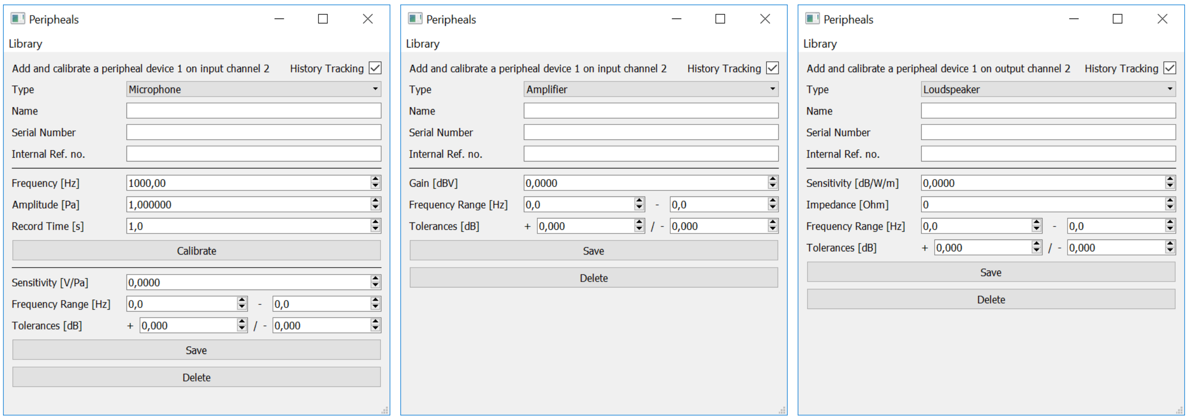


Figure C.3: Screenshot of the peripheral setup menu.

6. One channel is to be selected as the reference channel (loopback), used for compensating any introduced delay and characteristics by the sound card.

7. All microphones should be calibrated using an Bruel & Kjær 4231 acoustical calibrator or similar calibrator complying with IEC 60942 [IEC 60942, 2017] and follow a procedure

similar to the input calibration method except the signal is specified in pascal. This is seen on figure C.4a



(a) Specify all microphone specifications and calibrate it.

(b) Specify all amplifier settings.

(c) Specify all loudspeaker settings.

Figure C.4: Screenshot of three different peripherals which can be connected to the sound card.

8. Save the workspace for future use using the toolbar located in the top left corner of the main window.

By now the workspace is calibrated and saved in a configuration file. The workspace can be loaded at any time enabling for easy continuation of measurements in another location or room.

Measurement Report Template Creation

To increase the efficiency when noting equipment not used directly in the measurement chain a documentation template can be created. Equipment not used in the measurement chain can be calibrators, laser measurement tools, oscilloscopes and alike. Furthermore the template includes additional methods and the general information about the people responsible for the measurements. To create a template, the following procedure is to be followed:

1. Select the *Documentation*-tab in the BAMPI-program and navigate to the *General*-tab as shown on figure C.5.

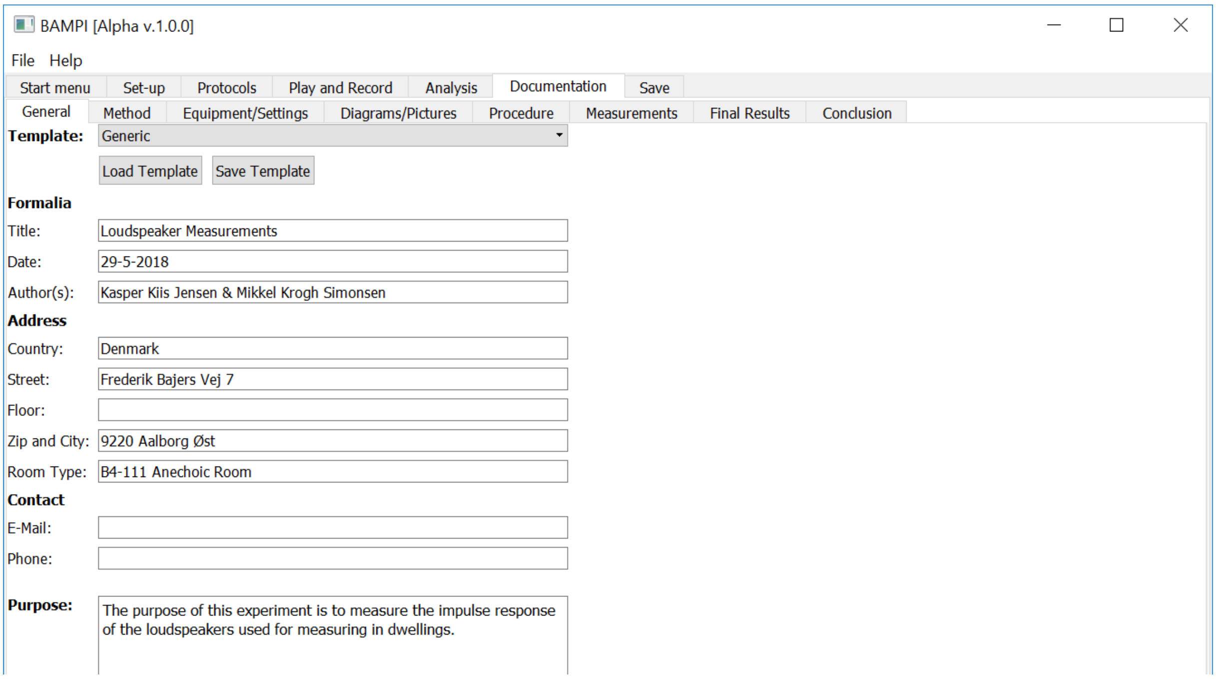


Figure C.5: Screenshot of the General - documentation-tab.

2. Select the desired measurement reporting template, e.g. ISO 3382-2. Note that a protocol specific template is only available when locked in the protocol tab.
    - The template will document all the noted values from the ISO *3382-2*-tab like microphone and source positions etc.
3. All general information is noted in the *General*-tab along with the purpose of the measurement.
4. In the *Method*-tab, shown on figure C.6 all extra methods is to be noted.

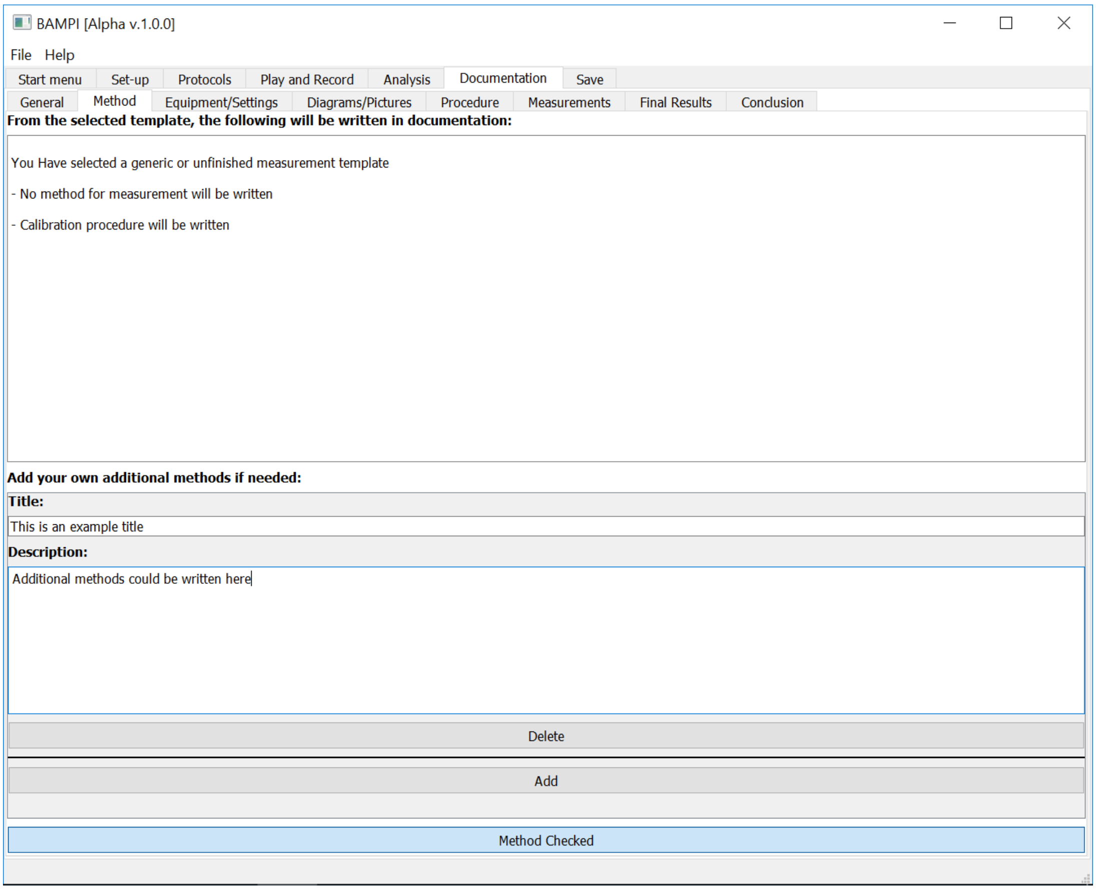


Figure C.6: Screenshot of the Method - documentation tab.

5. All additional equipment is noted in the *Equipment*-tab as shown on figure C.7. Already noted equipment in peripherals is shown for reference to ensure nothing is missed.
6. In the *General*-tab on figure C.5 the template is saved to a configuration file.

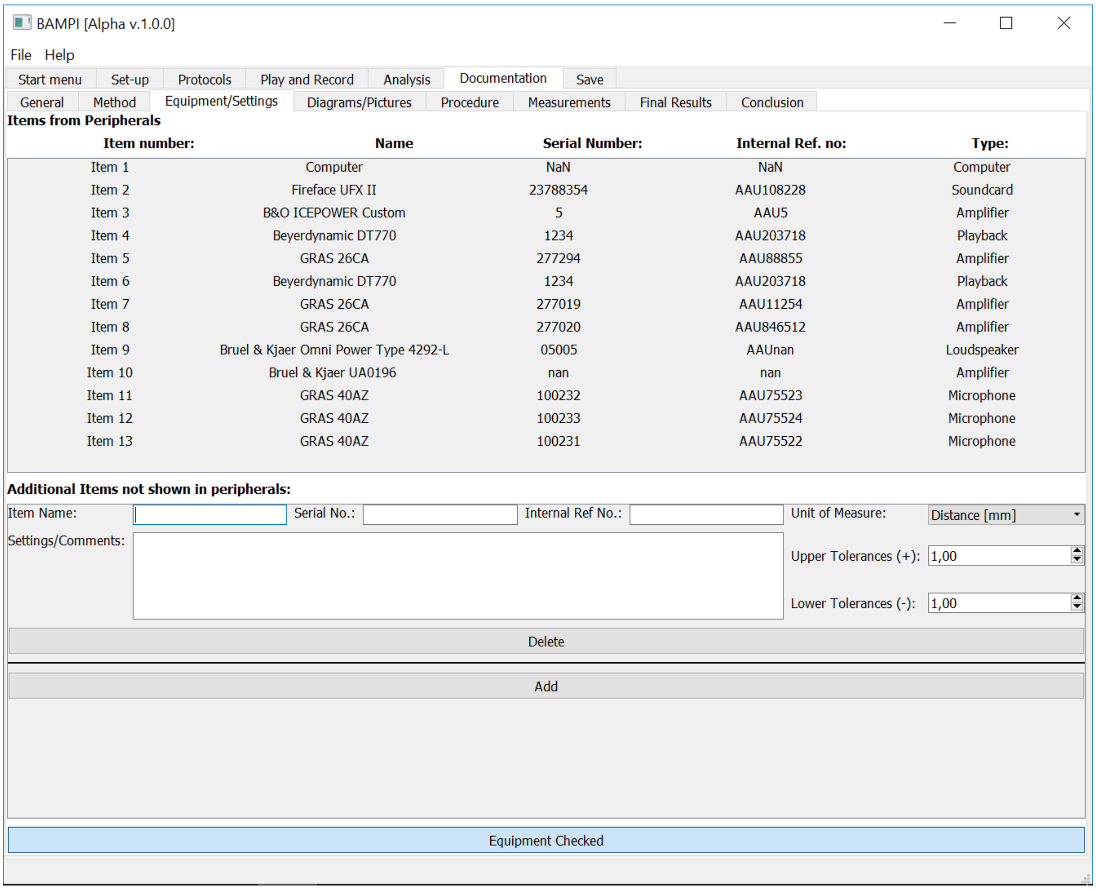


Figure C.7: Screenshot of the Equipment/Settings - documentation tab.

All the generic methods and additional equipment have now been noted for future use.

C.2 | Performing measurements using a workspace

By now all already known information have been noted in workspaces and template files. The procedure for acquiring a room impulse using the BAMPI software combined with workspace and template files, are as follows:

1. Start the BAMPI-system, select *Load Measurement Workspace*.
   - The system will automatically load all settings with regards to selected channel, peripheral devices and sensitivities.
2. Navigate to the *ISO 3382-2 protocol*-tab, shown in figure C.8, the following is to be noted:
   (a) The method "Integrated Impulse Response".
   (b) The precision method procedure.

(c) The lowest possible frequency range allowing for valid placement of microphones and source positions.

(d) An estimate of the reverberation is needed, this can either be done using the build-in estimation function or by subjectively determining the time based on an impulsive source like a clap.

(e) The rooms length, width and height.

- Only rectangular rooms are supported and the dimension is to be measured as the largest possible rectangle fitting the room, i.e. should a closet be present and not cover the entire wall partition, the point to measure from is behind the closet directly on the wall.

(f) The humidity and temperature in the room.

(g) All microphone and source positions.

- An interactive plot will display all positions with their required distance to boundary elements and each other based on the lowest frequency selected in previous step.
- The sources are to placed at locations where sound is normally emitted. At least one position should be in a corner if no normal use-case can be determined.
- In case of both kitchen and living room being in the same room, e.g. figure C.9b, the same room should be measured twice with source positions located within the area devoted to either kitchen or living room. Microphone positions should still be random throughout the room but different from each "room".
- In case of semi-separable rooms, e.g. figure C.9a, the two areas should be measured as individual rooms separated where a partition would most likely be, keeping all microphones and source positions confined within their respective area.
- Microphones should be placed as random as possible and as far away as possible while trying to avoid symmetric positioning.

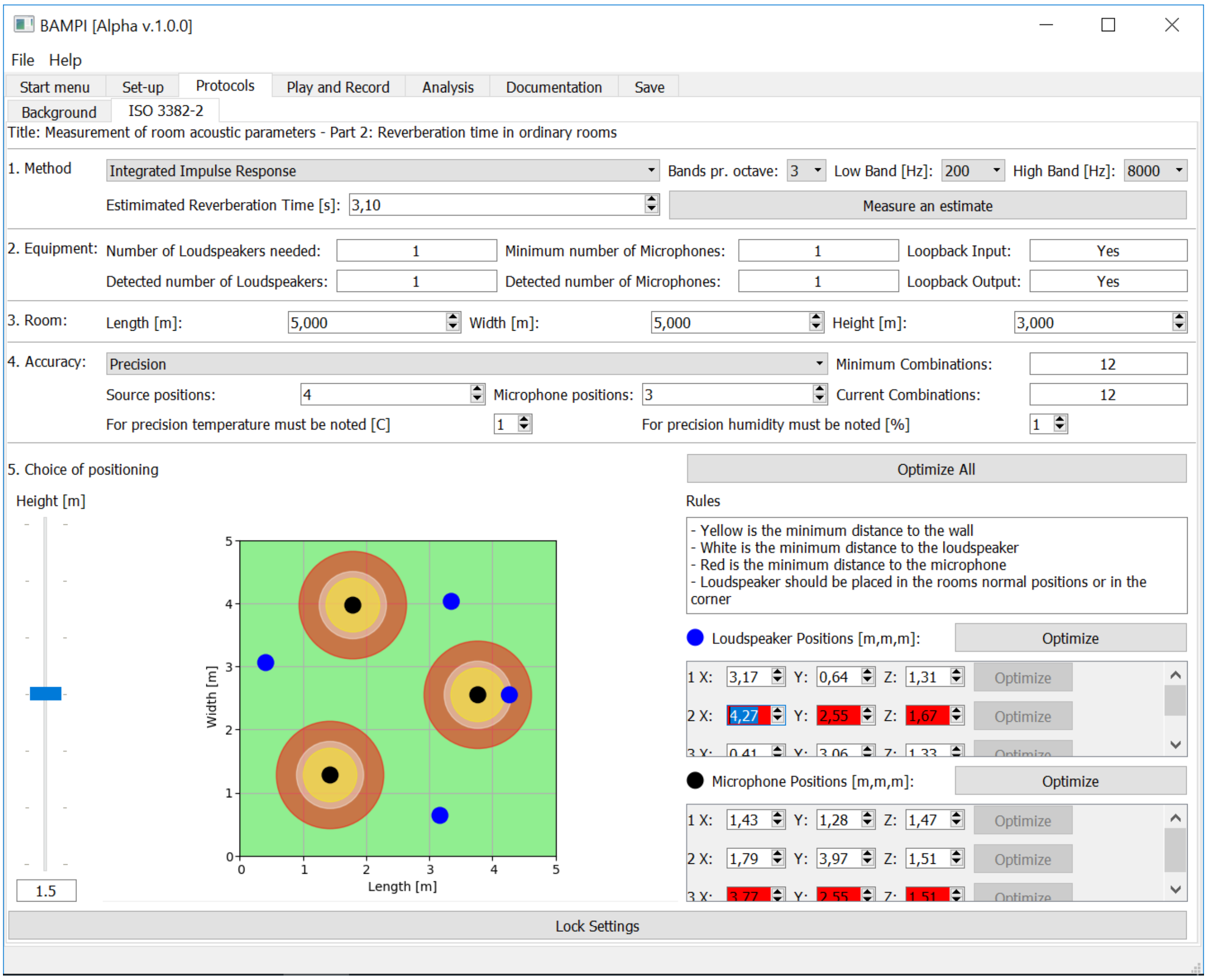
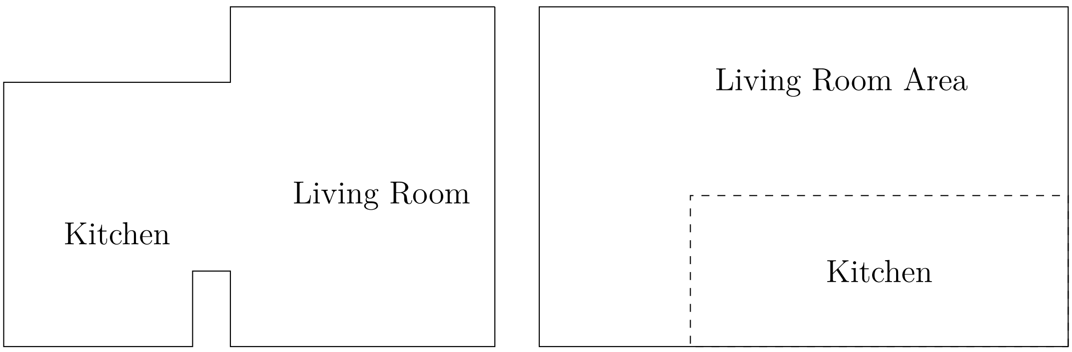


Figure C.8: Screenshot of the 3382-2 protocol menu.



(a) Kitchen and living room dividable into two rooms situations.

(b) Kitchen and living room combined in one room with no clear separation.

Figure C.9: Example of two different combined rooms.

3. Lock settings in the ISO 3382-2 protocol tab
   - If any constraints are violated the program will prompt the user prior to locking the setup.
   - All violated constraints are shown with red overlay in their respective box.
4. Upon locking the BAMPI system automatically generates ISO 18233 and 3382 compliant logarithmic sweeps for all loudspeakers based on the noted frequency range.

5. Navigate to the *Play and Record*-tab, shown in figure C.10.
6. Perform the prescribed measurement displayed in the procedure window, applying the following sub-procedure to each measurement:
   (a) Check levels before measuring. BAMPI shows and estimate of the sound pressure level based on the set specifications and gain values throughout the playback chain. A warning will be given if the voltage exceeds the recommended level and potentially introduce clipping of the signal [IEC 60268-11, 1987]. Playback levels shall be at least 30 dB above noise floor, if not redo the measurement with increased gain.
   (b) The information box on the right hand side will display the following information throughout the measurements:
      - When the measurement starts and end.
      - All individual bands with a linear fit deviating more than 10% from the decay curve.

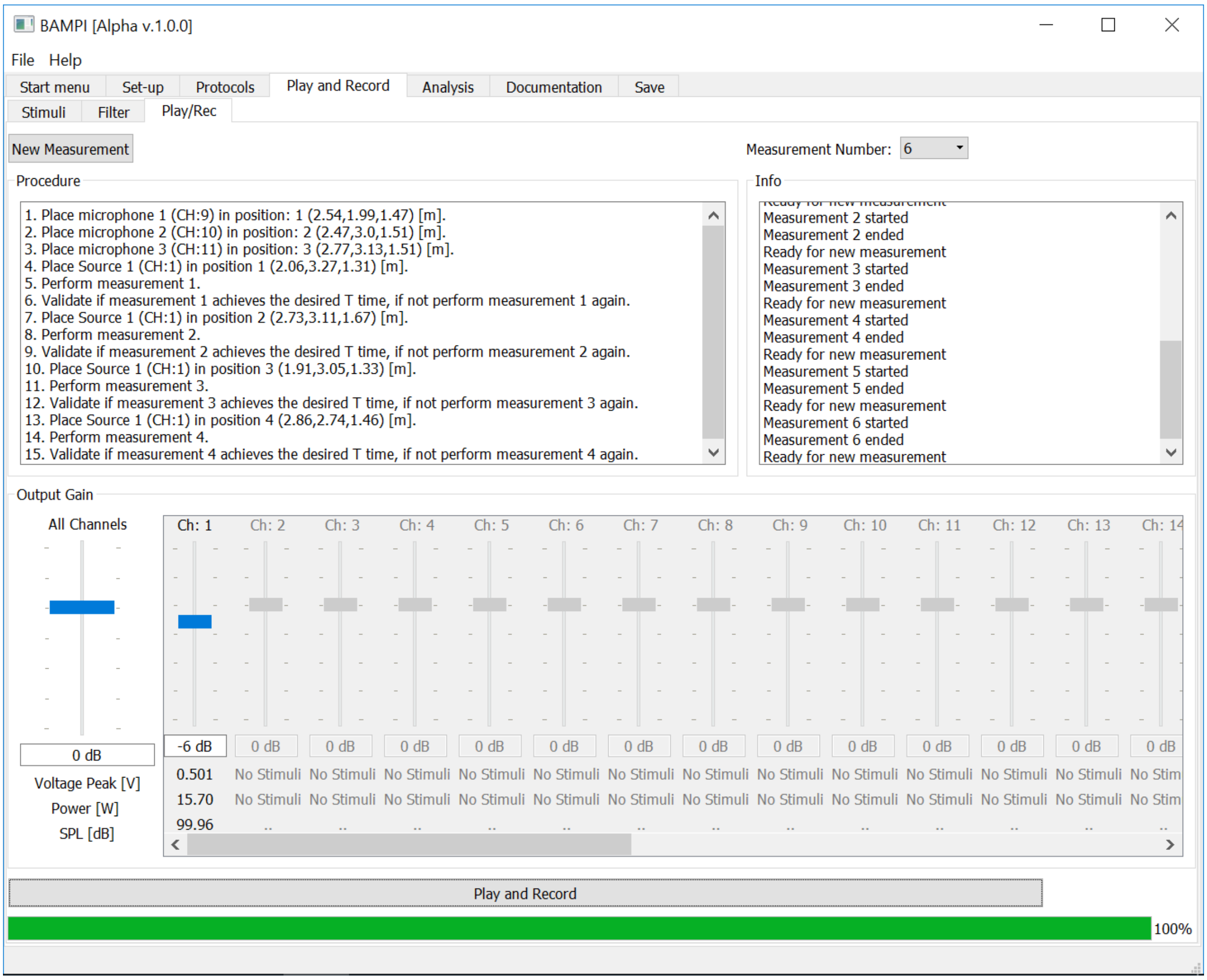


Figure C.10: Screenshot of the Play and Record menu.

(c) When a measurement is done, impulse responses for each channel is calculated using linear deconvolution and then filtered using IEC 61260 compliant octave bands [IEC 61260-1, 2014]. Each filtered impulse is then backwards integrated to create a decay curve [Schroeder, 1965]. Valid T20 values is essential and will help ensure a reasonable SNR for the measurement. This is done in the *Decay Curve*-tab located in the *Analysis*-tab, shown in figure C.11.

- All T-times deviating less than 1‰ T-times will be displayed with a green label and are suitable for calculating reverberation time.
- All T-times deviating more than 1‰ but less than 10‰ is displayed with a yellow label and can be suitable for calculating reverberation time.
- All T-times deviating more than 10‰ is displayed with a orange label and should be checked if it's linear enough for calculating a reverberation time. This is done with visual inspections. If the time isn't valid, the measurement should be run again at increased level if possible.
- All orange T20 times must be documented using the "Add to documentation"

button under the respective analysis.

– All T-times which does not reach an SNR greater than what's needed for determining a T-time is displayed with a red label and should be run again the band is desired.

(d) If an unexplained and/or unsolvable phenomena arises which is not solvable with repetitive measurement it is to be added to the documentation using the "Add to documentation" button under the respective analysis.

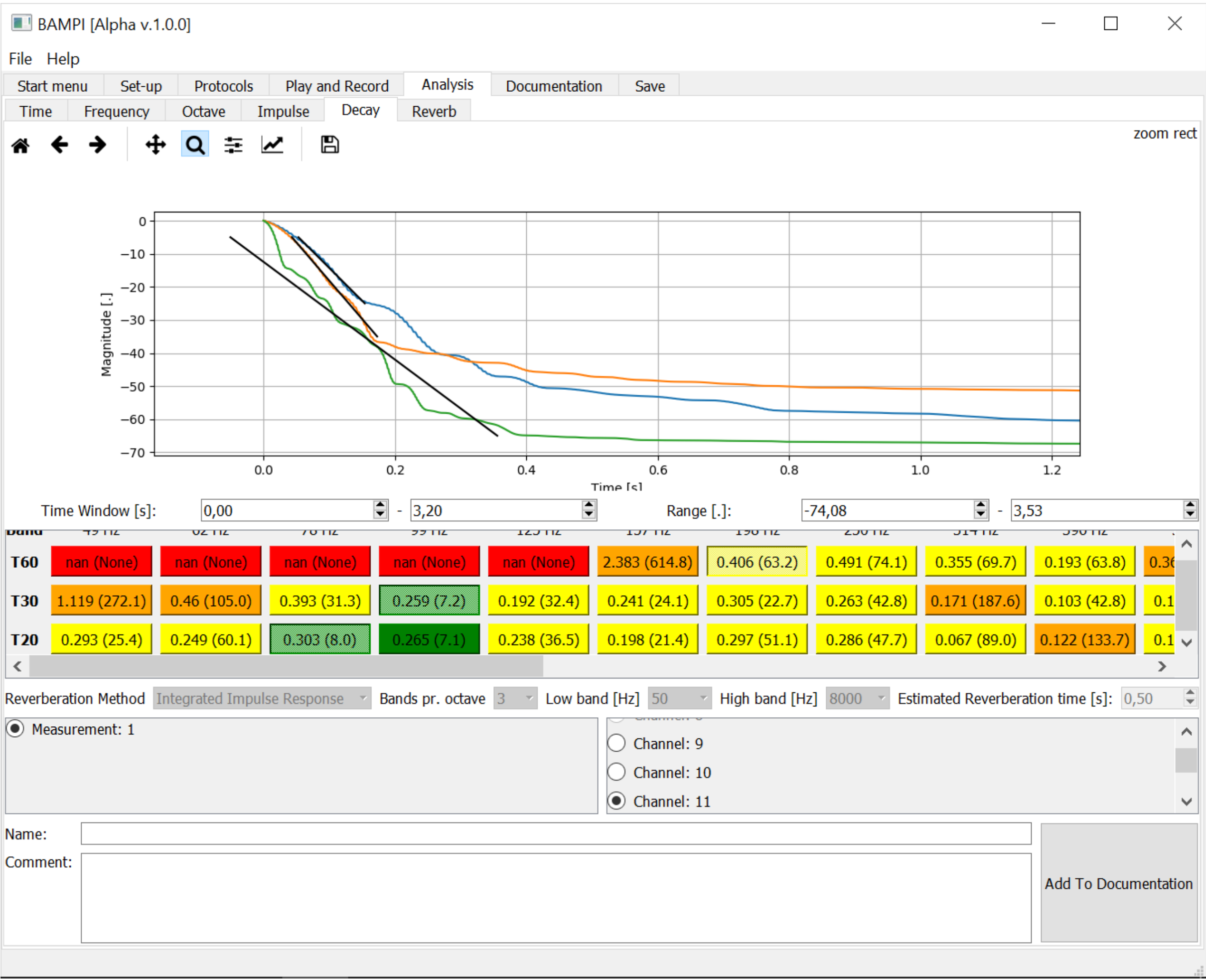


Figure C.11: Screenshot of the Decay curve analysis tab.

7. In the *documentation*-tab. Select the desired documentation template, in this case ISO3382-2.

8. To document all the standard equipment used a template can be loaded documenting calibrators, laser distance meters, oscilloscopes and alike.

9. Any anomalies present during the measurements are to be documented for each measurement in their respective comment field.

10. All information elaborating the surroundings is documented via pictures.
    - Minimum picture documentation is to cover all wall partitions along with ceiling and flooring.
    - Each picture is to receive a caption describing construction material.
11. Conclude on the entire measurement and note, if any, error sources.
12. Select the desired save format .mat for Matlab and amount of documentation in the save tab as shown on figure C.12.

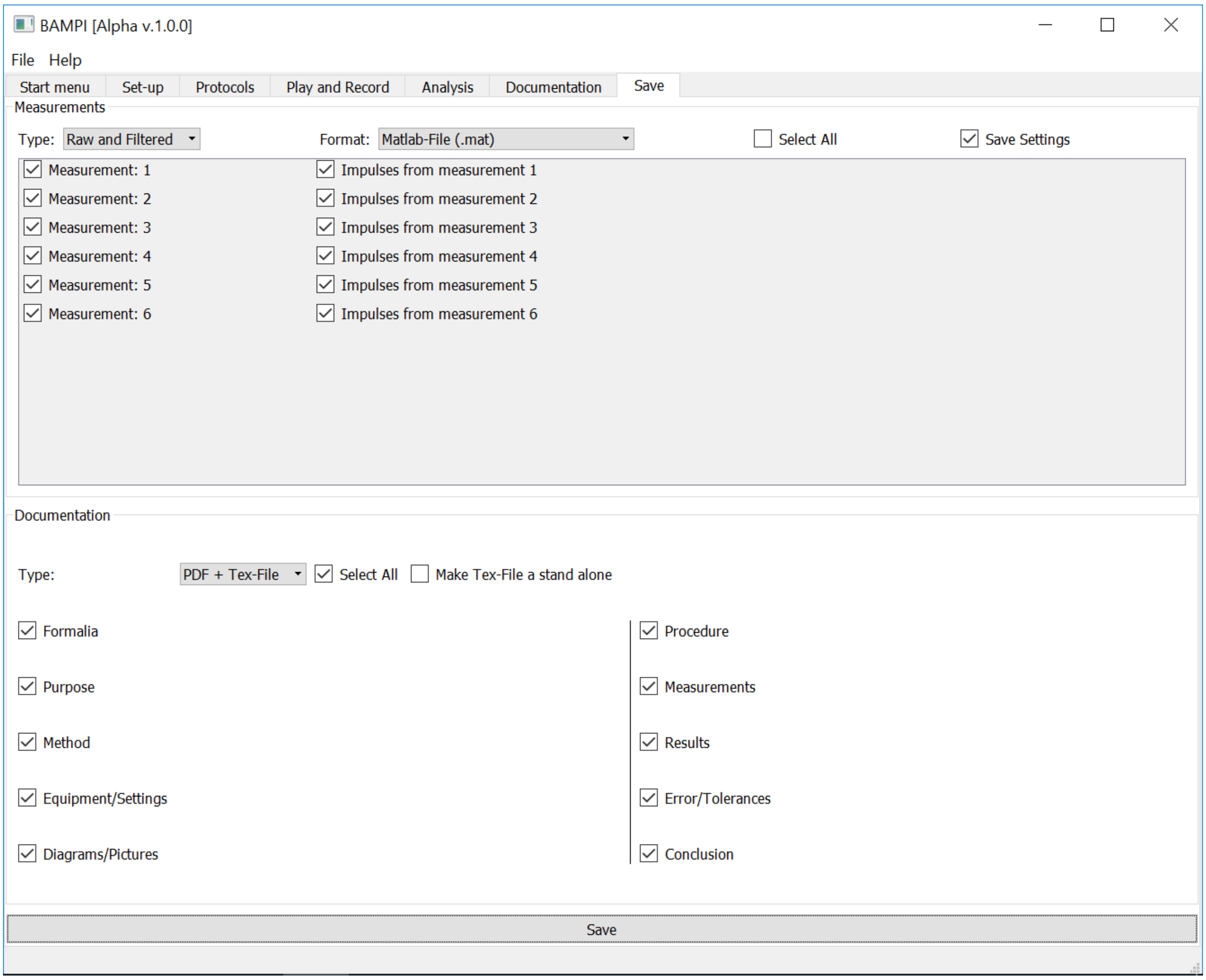


Figure C.12: Screenshot of the save tab.

When the measurements are done and the above procedure has been followed and a saved folder has been created containing the following information:

- Calibrated raw and filtered measurements.

- All settings values for both sound card and peripherals.
- Complete documented measurement report.
- All Pictures and individual graphs displayed the report.

The complete file structure can be seen on figure C.13

```
Measurement XX
├ Data
│  ├─ Impulses.mat
│  ├─ Measurements.mat
│  └─ Results.mat
├ Pictures
│  ├─ Picture XX.jpg
│  └─ ...
├ Settings
│  ├─ GainSettings.mat
│  ├─ TemplateSettings.ini
│  └─ Workspace.ini
├─ Report.pdf
└─ Results.pdf
```

Figure C.13: File structure of a saved measurement.

All information is made traceable with time stamps and reference number to all peripherals. An example of a complete measurement report can be seen in Appendix D

D | BAMPI Measurement Report

A .pdf version of the report can be found at `CD:/ExampleReport.pdf`

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Contact Information:
Mikkel Simonsen and Kasper Jensen
Mail: Mksi13@student.aau.dk and Kkje13@student.aau.dk
Phone: 40637317 and 21444475

Location:
[redacted]
Kitchen

Contents

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1 Purpose

The purpose of this measurement is to conduct a ISO3382-2 precision test.

2 Method

This section describes the different methods used throughout the set up and measurements.

2.1 ISO 3382-2

This measurement report was created to document an ISO 3382-2 measurement using Precision Method. However the requirements for positioning of loudspeakers and microphones was, according to ISO 3382-2 [1], not met at the specified freuqency range of 50 Hz to 8000 Hz.

2.2 Calibration

This section decribes how the calibration procedure was performed. All procedures are handled by the BAMPI interface, with the user only specifying either record time or frequency of interest.

2.2.1 Inputs

The inputs was not calibrated during these measurements, but loaded from a workspace. Detailed calibration information is noted in section 3.2.

2.2.2 Outputs

The outputs was not calibrated during these measurements, but loaded from a workspace.Detailed calibration information is noted in section3.2.

2.2.3 Microphones

No microhpone was calibrated during these measurements, but loaded from a workspace. Detailed calibration information is noted in section 3.2.

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3 Equipment and Settings

This section contains all equipment used for performing the measurements. Table 1 lists the equipment used.

3.1 Equipment List

Item no.	Description/Name	Serial no.	Internal reference no.
1	Computer with Windows 8.1 and version 1.0.0 of BAMPI.	NaN	NaN
2	Fireface UFX II	23788354	AAU108228
3	B&O ICEPOWER Custom	5	AAU5
4	Beyerdynamic DT770	1234	AAU203718
5	Bruel & Kjaer Omni Power Type 4292-L	05005	AAUnan
6	GRAS 26CA	277294	AAU88855
7	GRAS 26CA	277019	AAU11254
8	GRAS 26CA	277020	AAU846512
9	GRAS 40AD	73551	AAU99756
10	GRAS 40AD	252624	AAU108219
11	GRAS 40AD	252648	AAU108210
12	Brüel Kjaer Acoustical Calibrator Type 4231	2115338	AAU33691
13	Analog Discovery 2	DA2A9BA	217310
14	Leica Disto D2	258963	AAU2157-64
15	KM 8004	3693	AAU33192

Table 1: List of equipment.

3.2 Settings

This section contains all settings chosen for the performed measurements.

Bold dates	describes denotes a value calibrated during the measurement.
Regular date	denotes a value loaded from a workspace file with defined calibration values.
Italic Dates	describes a value that has been manually altered by a user.

Soundcard and Computer

The sound card is configured with the following settings:

Samplerate	48000
Buffer size	1024
Driver	ASIO

The measurements were performed on a computer with Windows 8.1 and version 1.0.0 of BAMPI. By selecting ASIO driver it is ensured that any additional audio driver installed does not intefere with recordings or playback [2]. The Buffer size is set to 1024.

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Input and Output Sensitivity

Input no.	Gain $\frac{Number}{volt}$ [dBFS]	Date of Calibration
1	-19.87	4/5/2018
9	-19.12	4/5/2018
10	-19.13	4/5/2018
11	-19.12	4/5/2018

(a) Input sensitivity.

Output no.	Gain $\frac{volt}{number}$ [dBFS]	Date of Calibration
1	7.72	4/5/2018
9	19.75	5/5/2018
10	19.76	5/5/2018

(b) Output sensitivity.

Table 2: Input and Output gains with the respective sensitivity and date of calibration.

Microphones

Item no.	Name	Channel	Sensitivity $[\frac{mV}{Pa}]$	Date of calibration
9	GRAS 40AD	9	48.30	5/5/2018
10	GRAS 40AD	10	46.70	5/5/2018
11	GRAS 40AD	11	49.50	5/5/2018

Table 3: All microphones used with their respective sensitivity, channel location and calibration date.

Amplifiers

Item no.	Name	Channel	Gain $[dBV]$
6	GRAS 26CA	9	-0.30
7	GRAS 26CA	10	-0.30
8	GRAS 26CA	11	-0.30
3	B&O ICEPOWER Custom	1	30.00

Table 4: All amplifiers for both input and output used along with their respective gain and channel location

Transducers

Item no.	Name	Channel	Sensitivity
4	Beyerdynamic DT770	9	96.00 [dB SPL/mW]
4	Beyerdynamic DT770	10	96.00 [dB SPL/mW]
5	Bruel & Kjaer Omni Power Type 4292-L	1	88.00 [dB SPL/W/m]

Table 5: All loudspeakers and headphones with their respective sensitivity and channel location.

Additional Equipment

Item no.	Name	Settings/Comments
12	Brüel Kjaer Acoustical Calibrator Type 4231	Used to calibrate all microphones.
13	Analog Discovery 2	Used to calibrate soundcards
14	Leica Disto D2	Used to measure room and positions
15	KM 8004	Used to measure temperature and humidity

Table 6: All additional equipment which is not visible on figure 1.

4 Diagrams and Pictures

4.1 Peripheral Connections

This section describes the different connections to the soundcard and all the peripherals used. It should be noted that the wirings on figure 1 is not noted with the specific type of cable used.

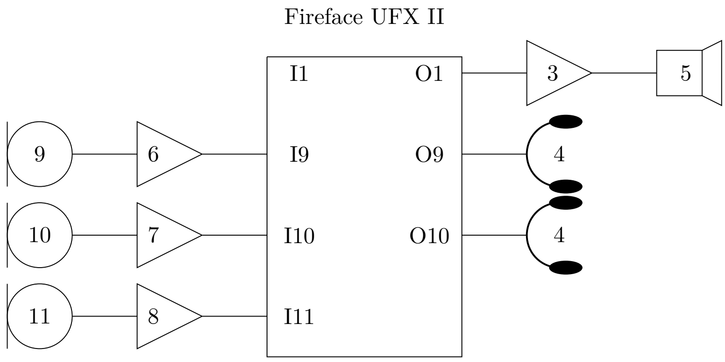
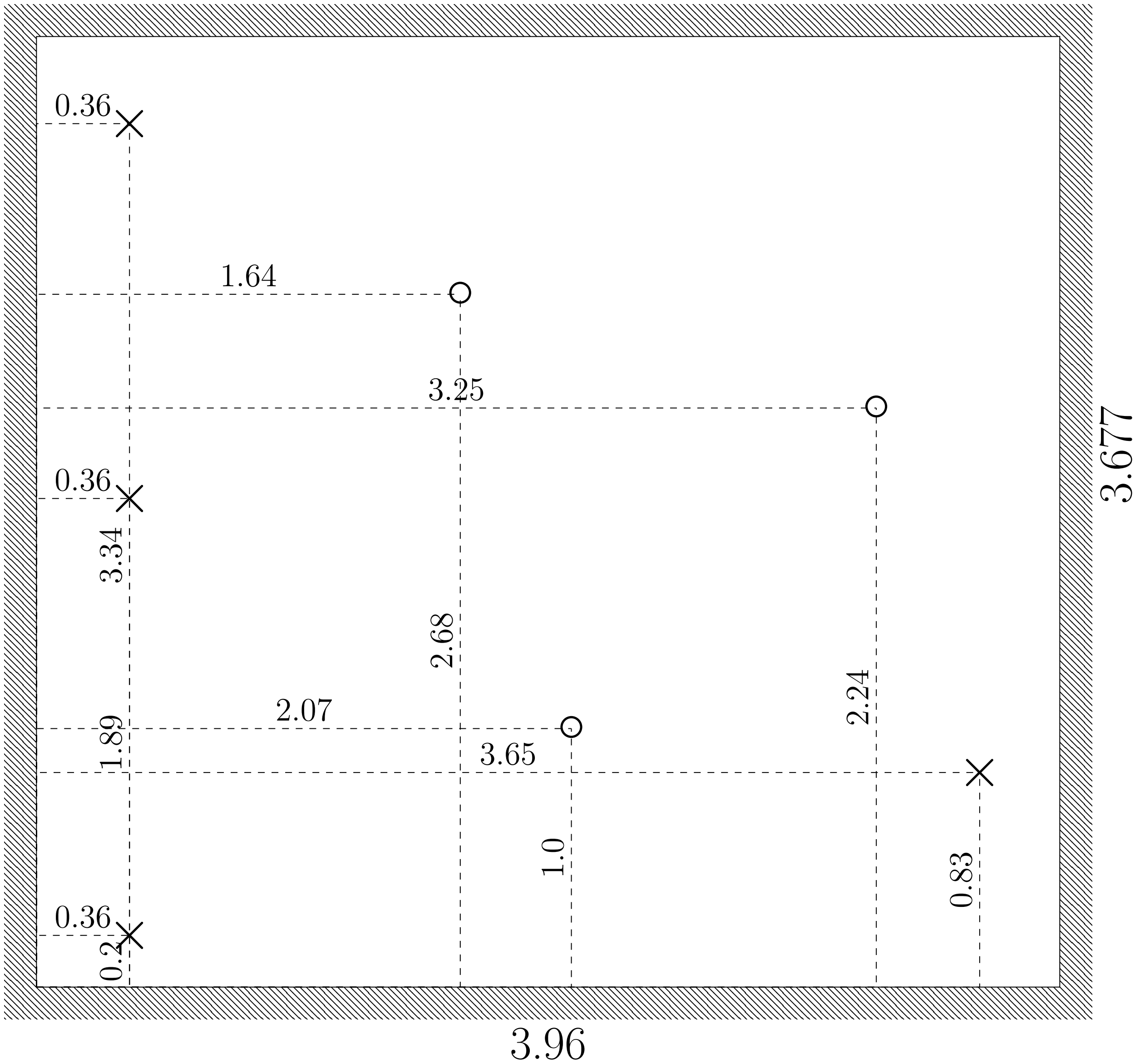


Figure 1: Schematic of the soundcard and all connected periperals.

Output channel 1 is connected to input channel 1 and is used as reference signal

4.2 Microphone and Source Position



(a) Graphical representation of microphone and source positions. The room height is 2.57m.

Positions	X [m]	Y [m]	Z [m]
Microphone 1	1.64	2.68	1.44
Microphone 2	3.25	2.24	1.50
Microphone 3	2.07	1.00	1.82
Source 1	3.65	0.83	1.82
Source 2	0.36	1.89	1.40
Source 3	0.36	0.20	1.80
Source 4	0.36	3.34	1.40

(b) List of microphone and loudspeaker positions.

Figure 2: All distances are noted in meters. Sources are noted × and microphones ∘.

5 Pictures

Figure 3: Picture 1 of room. The midlle wall is plaster and the back wall is concrete.

Figure 4: Picture 2 of room. The middle wall is plaster.

Figure 5: Picture 3 of room. The back wall is tiles on concrete.

Figure 6: Picture 4 of room. The wall is concrete.

6 Procedural check list

1. Place microphone 1 (CH:9) in position: 1 (1.64,2.68,1.44) [m].
2. Place microphone 2 (CH:10) in position: 2 (3.25,2.24,1.5) [m].
3. Place microphone 3 (CH:11) in position: 3 (2.07,1.0,1.82) [m].
4. Place Source 1 (CH:1) in position 1 (3.65,0.83,1.82) [m].
5. Perform measurement 1.
6. Validate if measurement 1 achieves the desired T time, if not perform measurement 1 again.
7. Place Source 1 (CH:1) in position 2 (0.36,1.89,1.4) [m].
8. Perform measurement 2.
9. Validate if measurement 2 achieves the desired T time, if not perform measurement 2 again.
10. Place Source 1 (CH:1) in position 3 (0.36,0.2,1.8) [m].
11. Perform measurement 3.
12. Validate if measurement 3 achieves the desired T time, if not perform measurement 3 again.
13. Place Source 1 (CH:1) in position 4 (0.36,3.34,1.4) [m].
14. Perform measurement 4.
15. Validate if measurement 4 achieves the desired T time, if not perform measurement 4 again.

7 Measurements

All measurements were done with an ambient temperature of 23 degrees celcius and 35 % relative humidity Table 7 denotes the gains settings applied by the user during the measurements.

Output Channel	Gain Setting [dB]
1	-6.0
9	0.0
10	0.0

Table 7: Gain values specified by user.

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7.1 Measurement 1

Stimuli

During measurement 1, the following stimuli was used on their respective channels. All sweeps are synthesized in frequency [3]

- Channel 1: Settings for Stimuli: Sweep - Type: Log - Time: 5.0 - Frequency Range: 50.0-12000.0, Degree of Linearty: 99.77 %, Zero padding before 0.0 [s] and after 2.5 [s]

Filter Settings (Inputs)

- Channel 9: Filter Settings: LP: Passband 0.1 [dB] @ 9878.0 [Hz], Stopband 20.0 [dB] @ 16000.0 [Hz], HP Passband 0.1 [dB] @ 40.0 [Hz], Stopband 20.0 [dB] @ 25.0 [Hz]
- Channel 10: Filter Settings: LP: Passband 0.1 [dB] @ 9878.0 [Hz], Stopband 20.0 [dB] @ 16000.0 [Hz], HP Passband 0.1 [dB] @ 40.0 [Hz], Stopband 20.0 [dB] @ 25.0 [Hz]
- Channel 11: Filter Settings: LP: Passband 0.1 [dB] @ 9878.0 [Hz], Stopband 20.0 [dB] @ 16000.0 [Hz], HP Passband 0.1 [dB] @ 40.0 [Hz], Stopband 20.0 [dB] @ 25.0 [Hz]

T20-Values

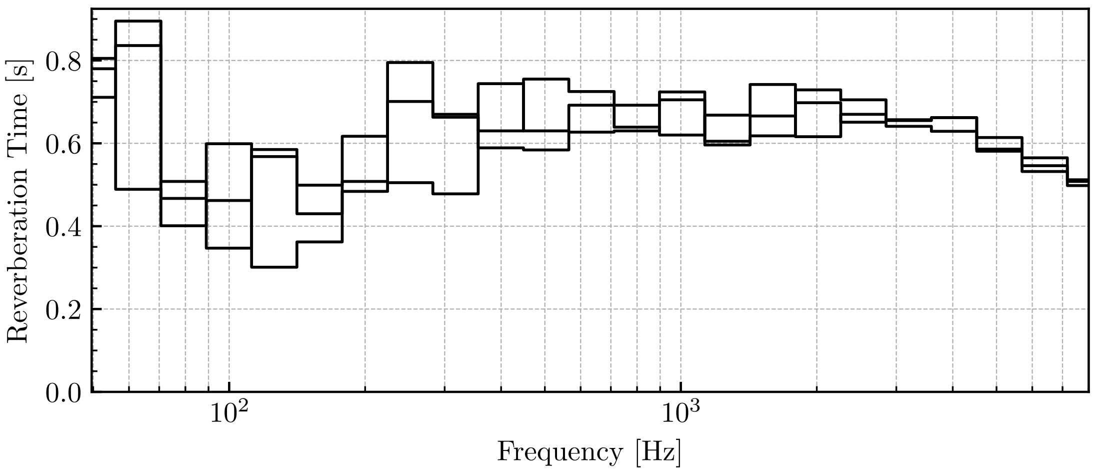

Figure 7: T20 values for measurement 1

Analysis of measurement 1

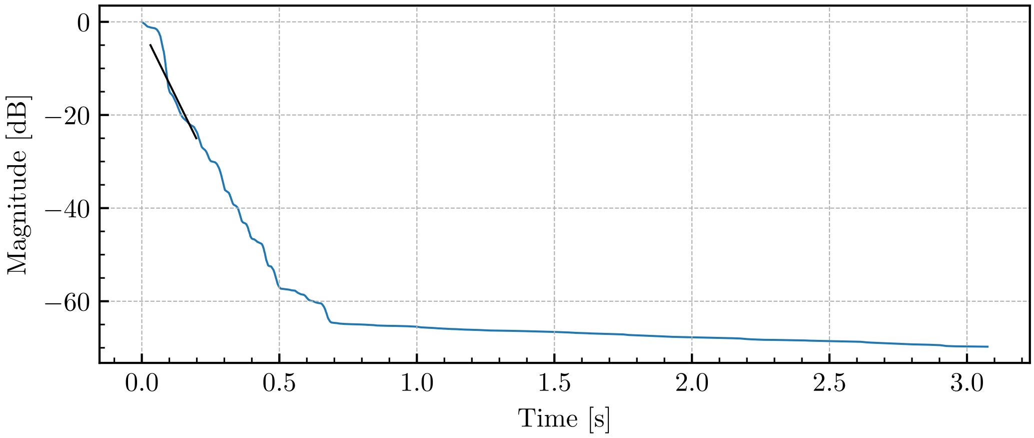

Figure 8: Decay curve of input CH9 band 157 Hz (●) (T20=0.499 [s]) using interrupted noise method.

The decay curve is not linear enough. The T20 time looks okay.

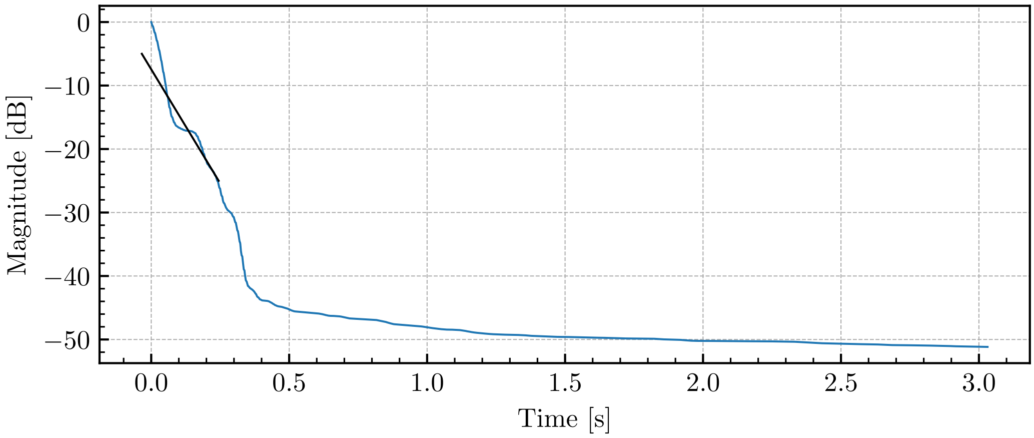

Figure 9: Decay curve of input CH10 band 62 Hz (●) (T20=0.836 [s]) using interrupted noise method.

The decay curve is not linear enough. The T20 time looks high.

7.2 Measurement 2

Stimuli

During measurement 2, the following stimuli was used on their respective channels. All sweeps are synthesized in frequency [3]

- Channel 1: Settings for Stimuli: Sweep - Type: Log - Time: 5.0 - Frequency Range: 50.0-12000.0, Degree of Linearty: 99.77 %, Zero padding before 0.0 [s] and after 2.5 [s]

Filter Settings (Inputs)

- Channel 9: Filter Settings: LP: Passband 0.1 [dB] @ 9878.0 [Hz], Stopband 20.0 [dB] @ 16000.0 [Hz], HP Passband 0.1 [dB] @ 40.0 [Hz], Stopband 20.0 [dB] @ 25.0 [Hz]
- Channel 10: Filter Settings: LP: Passband 0.1 [dB] @ 9878.0 [Hz], Stopband 20.0 [dB] @ 16000.0 [Hz], HP Passband 0.1 [dB] @ 40.0 [Hz], Stopband 20.0 [dB] @ 25.0 [Hz]
- Channel 11: Filter Settings: LP: Passband 0.1 [dB] @ 9878.0 [Hz], Stopband 20.0 [dB] @ 16000.0 [Hz], HP Passband 0.1 [dB] @ 40.0 [Hz], Stopband 20.0 [dB] @ 25.0 [Hz]

T20-Values

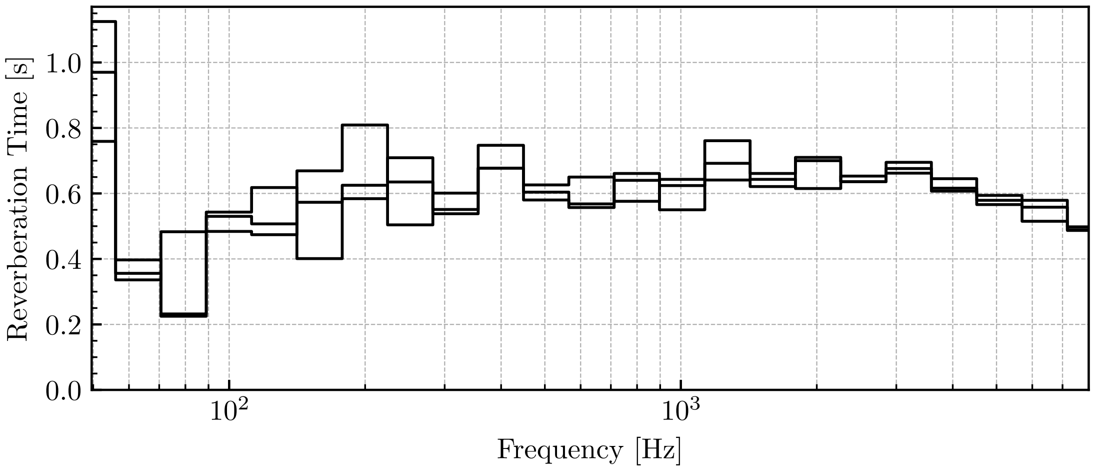

Figure 10: T20 values for measurement 2

Analysis of measurement 2

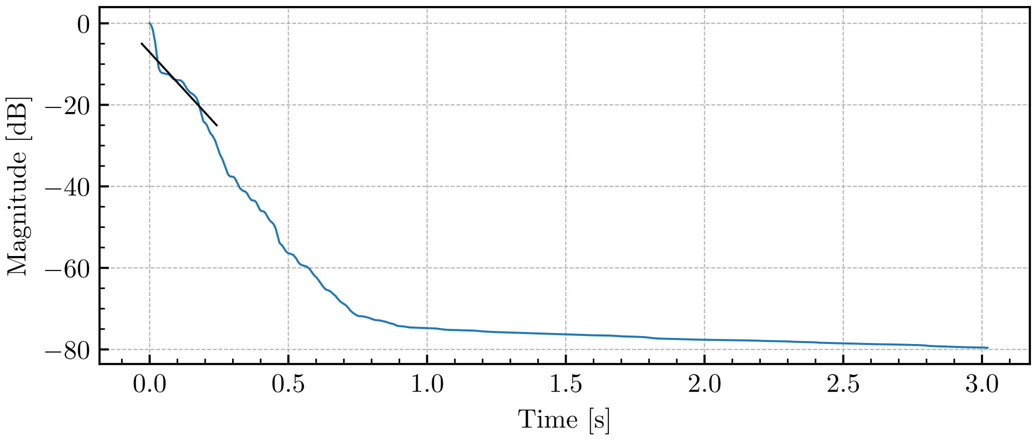

Figure 11: Decay curve of input CH9 band 198 Hz (●) (T20=0.809 [s]) using interrupted noise method.

The decay curve is not linear enough. The T20 time looks high.

7.3 Measurement 3

Stimuli

During measurement 3, the following stimuli was used on their respective channels. All sweeps are synthesized in frequency [3]

- Channel 1: Settings for Stimuli: Sweep - Type: Log - Time: 5.0 - Frequency Range: 50.0-12000.0, Degree of Linearty: 99.77 %, Zero padding before 0.0 [s] and after 2.5 [s]

Filter Settings (Inputs)

- Channel 9: Filter Settings: LP: Passband 0.1 [dB] @ 9878.0 [Hz], Stopband 20.0 [dB] @ 16000.0 [Hz], HP Passband 0.1 [dB] @ 40.0 [Hz], Stopband 20.0 [dB] @ 25.0 [Hz]
- Channel 10: Filter Settings: LP: Passband 0.1 [dB] @ 9878.0 [Hz], Stopband 20.0 [dB] @ 16000.0 [Hz], HP Passband 0.1 [dB] @ 40.0 [Hz], Stopband 20.0 [dB] @ 25.0 [Hz]
- Channel 11: Filter Settings: LP: Passband 0.1 [dB] @ 9878.0 [Hz], Stopband 20.0 [dB] @ 16000.0 [Hz], HP Passband 0.1 [dB] @ 40.0 [Hz], Stopband 20.0 [dB] @ 25.0 [Hz]

T20-Values

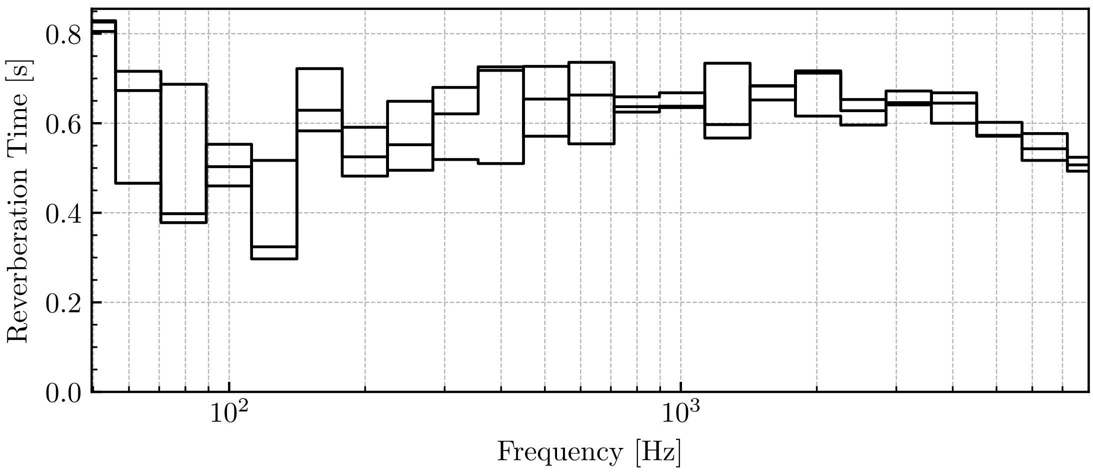

Figure 12: T20 values for measurement 3

Analysis of measurement 3

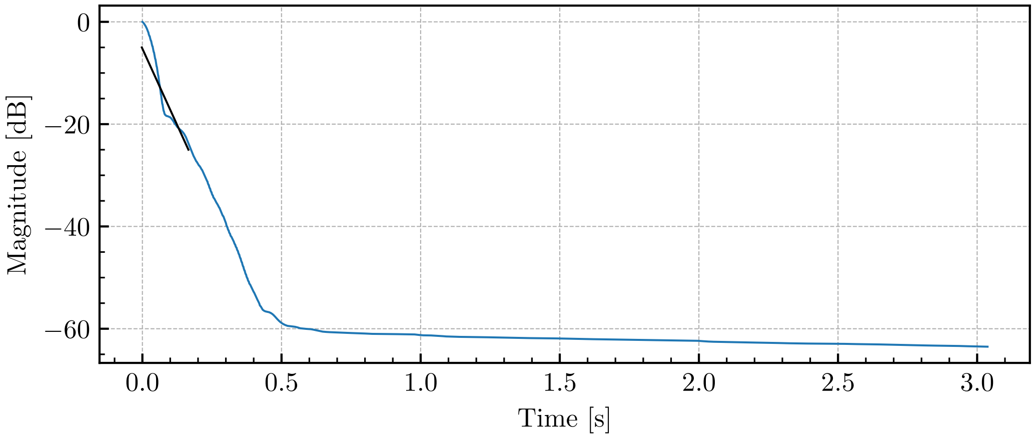

Figure 13: Decay curve of input CH9 band 99 Hz (●) (T20=0.503 [s]) using interrupted noise method.

The decay curve is not linear enough. The T20 time looks a little high.

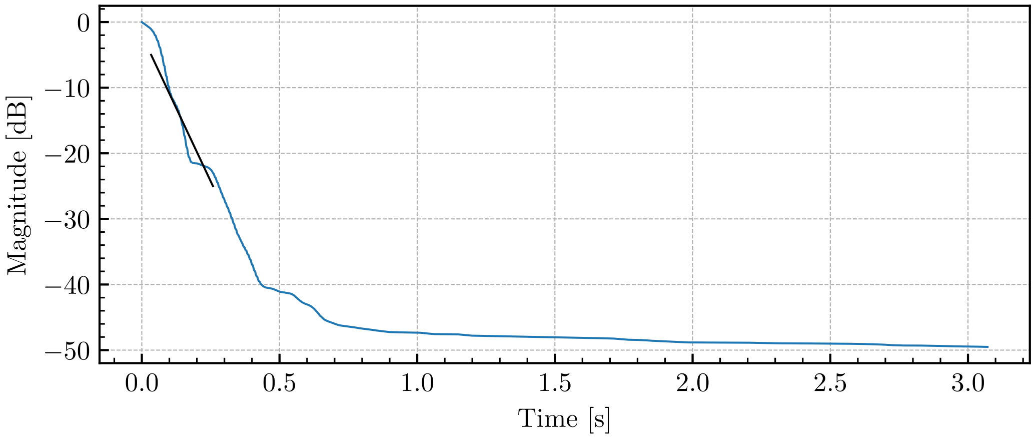

Figure 14: Decay curve of input CH11 band 62 Hz (●) (T20=0.673 [s]) using interrupted noise method.

The decay curve is not linear enough. The T20 time looks okay.

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7.4 Measurement 4

Stimuli

During measurement 4, the following stimuli was used on their respective channels. All sweeps are synthesized in frequency [3]

- Channel 1: Settings for Stimuli: Sweep - Type: Log - Time: 5.0 - Frequency Range: 50.0-12000.0, Degree of Linearty: 99.77 %, Zero padding before 0.0 [s] and after 2.5 [s]

Filter Settings (Inputs)

- Channel 9: Filter Settings: LP: Passband 0.1 [dB] @ 9878.0 [Hz], Stopband 20.0 [dB] @ 16000.0 [Hz], HP Passband 0.1 [dB] @ 40.0 [Hz], Stopband 20.0 [dB] @ 25.0 [Hz]
- Channel 10: Filter Settings: LP: Passband 0.1 [dB] @ 9878.0 [Hz], Stopband 20.0 [dB] @ 16000.0 [Hz], HP Passband 0.1 [dB] @ 40.0 [Hz], Stopband 20.0 [dB] @ 25.0 [Hz]
- Channel 11: Filter Settings: LP: Passband 0.1 [dB] @ 9878.0 [Hz], Stopband 20.0 [dB] @ 16000.0 [Hz], HP Passband 0.1 [dB] @ 40.0 [Hz], Stopband 20.0 [dB] @ 25.0 [Hz]

T20-Values

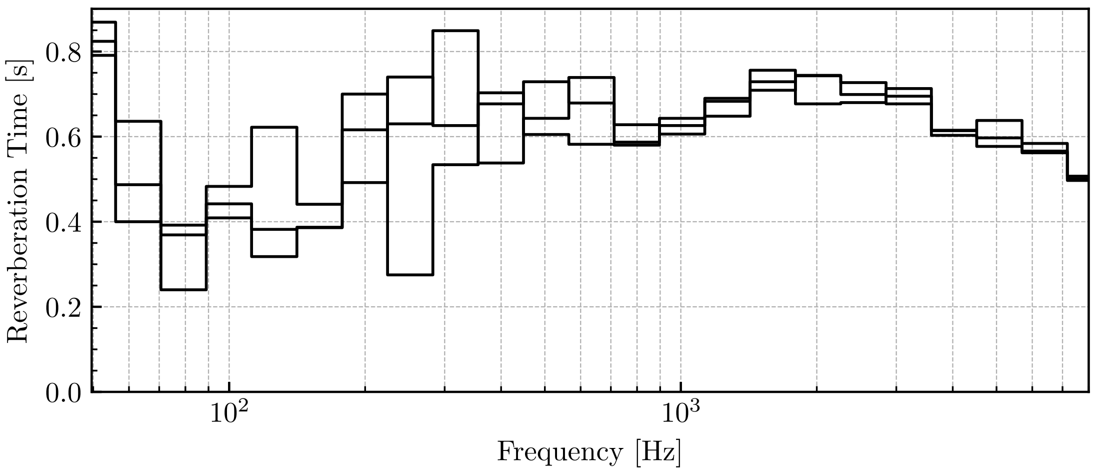

Figure 15: T20 values for measurement 4

Analysis of measurement 4

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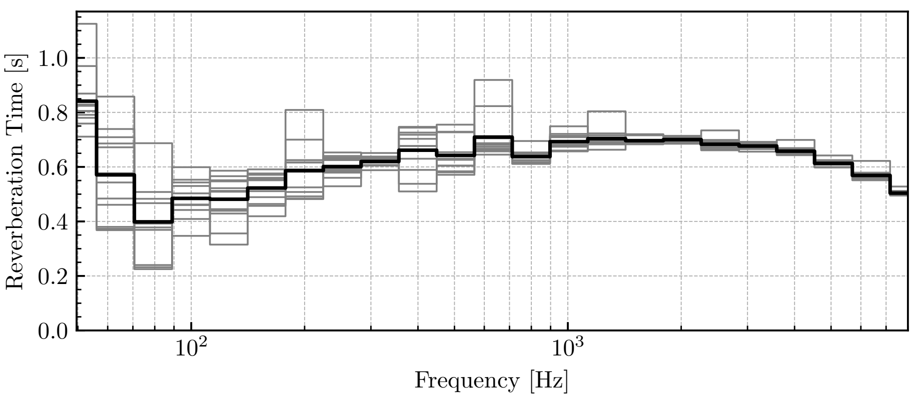
8 Results

Results acquired using Integrated Impulse Response method with Precision accuracy. Results are shown for T60, T30 and T20 with the number of measurements (N) used for averaging shown in the parentheses. The bold number in each band denotes the used reverberation time in the plot shown as the black curve, while the grey curves are individual measurements.

Frequency [Hz]	T60 [s] (N)	T30 [s] (N)	T20 [s] (N)
50	nan (0)	1.10 (4)	**0.84 (12)**
62	nan (0)	**0.57 (12)**	0.56 (12)
79	nan (0)	0.67 (12)	**0.40 (12)**
99	nan (0)	0.48 (12)	**0.48 (12)**
125	1.07 (9)	**0.48 (12)**	0.46 (12)
157	0.64 (12)	**0.52 (12)**	0.51 (12)
198	0.90 (12)	0.58 (12)	**0.59 (12)**
250	0.73 (12)	**0.60 (12)**	0.60 (12)
315	**0.62 (12)**	0.60 (12)	0.61 (12)
397	0.79 (12)	0.65 (12)	**0.66 (12)**
500	0.70 (12)	0.62 (12)	**0.64 (12)**
630	**0.71 (12)**	0.65 (12)	0.65 (12)
794	0.76 (12)	**0.64 (12)**	0.63 (12)
1000	**0.69 (12)**	0.64 (12)	0.64 (12)
1260	**0.70 (12)**	0.66 (12)	0.66 (12)
1587	**0.70 (12)**	0.68 (12)	0.68 (12)
2000	**0.70 (12)**	0.69 (12)	0.69 (12)
2520	**0.68 (12)**	0.67 (12)	0.66 (12)
3175	**0.68 (12)**	0.67 (12)	0.67 (12)
4000	**0.66 (12)**	0.64 (12)	0.63 (12)
5040	**0.61 (12)**	0.60 (12)	0.59 (12)
6350	**0.57 (12)**	0.55 (12)	0.55 (12)
8000	0.53 (9)	**0.50 (12)**	0.50 (12)



9 Tolerances

The following tables shows the tolerances of all noted equipment used for performing measurements. Table 8 is the input peripherals. Table 9 is the output peripherals. Additional equipment from exterior peripherals can be seen in table 10.

Item no.	Name	Tolerance [dB]	Frequency Area [Hz]
6	GRAS 26CA	+0.2/-0.2	2.5 - 20000.0
7	GRAS 26CA	+0.2/-0.2	2.5 - 20000.0
8	GRAS 26CA	+0.2/-0.2	2.5 - 20000.0
9	GRAS 40AD	+1.0/-1.0	12.5 - 7500.0
10	GRAS 40AD	+1.0/-1.0	12.5 - 7500.0
11	GRAS 40AD	+1.0/-1.0	12.5 - 7500.0

Table 8: All input peripherals used for performing measurements with their respective tolerances in the stated frequency area.

Item no.	Name	Tolerance [dB]	Frequency Area [Hz]
3	B&O ICEPOWER Custom	+1.0/-1.0	2.0 - 20000.0
4	Beyerdynamic DT770	+1.0/-1.0	5.0 - 35000.0
5	Bruel & Kjaer Omni Power Type 4292-L	+1.0/-1.0	50.0 - 12000.0

Table 9: All output peripherals used for performing measurements with their respective tolerances in the stated frequency area.

Item no.	Name	Tolerance	Unit of measurement
12	Brüel Kjaer Acoustical Calibrator Type 4231	+0.2/-0.2	[SPL]
13	Analog Discovery 2	+0.1/-0.1	[dBV]
14	Leica Disto D2	+1.0/-1.0	[mm]
15	KM 8004	+1.0/-1.0	[Celcius]

Table 10: All noted equipment not visible on figure 1 tolerances and unit of measure.

10 Error

The were 3 people in the living room which is open into the kitchen.

11 Conclusion

An ISO3382 precision method was carried out. All results are accepted on the basis of the ISO3382 requirements.

References

[1] DS/ISO 3382, "Acoustics – Measurement of room acoustic parameters - Part 2: Reverberation time in ordinary rooms," standard, International Organization for Standardization, Geneva, CH, juli 2008.

[2] Steinberg, "Asio interface," 2017. Downloaded 19/12-2017.

[3] S. Müller and P. Massarani, "Transfer-function measurement with sweeps," *J. Audio Eng. Soc*, vol. 49, no. 6, pp. 443–471, 2001.

E | BAMPI Result Example

A .pdf version of the report can be found at `CD:/ExampleResult.pdf`

ISO 3382-2 Result
5-5-2018

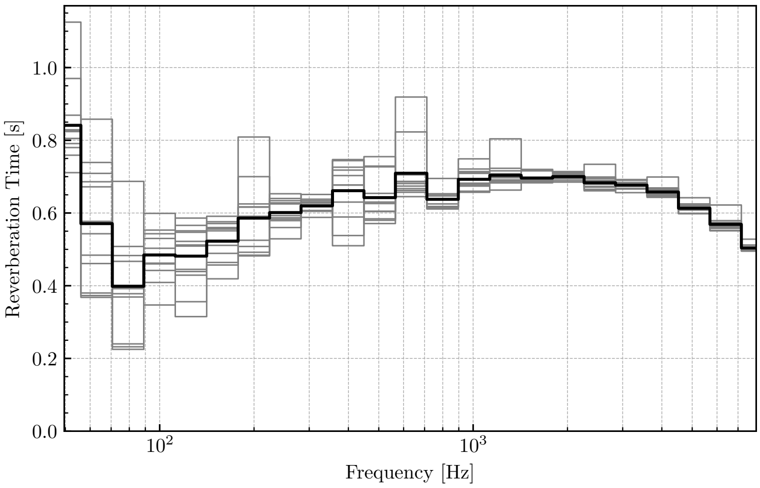
Contact Information:
Mikkel Simonsen and Kasper Jensen
Mail: Mksi13@student.aau.dk and Kkje13@student.aau.dk
Phone:40637317 and 21444475

Location:
[redacted]
Kitchen

Results

Results acquired using Integrated Impulse Response method with Precision accuracy. Results are shown for T60, T30 and T20 with the number of measurements (N) used for averaging shown in the parentheses. The bold number in each band denotes the used reverberation time in the plot shown as the black curve, while the grey curves are individual measurements.

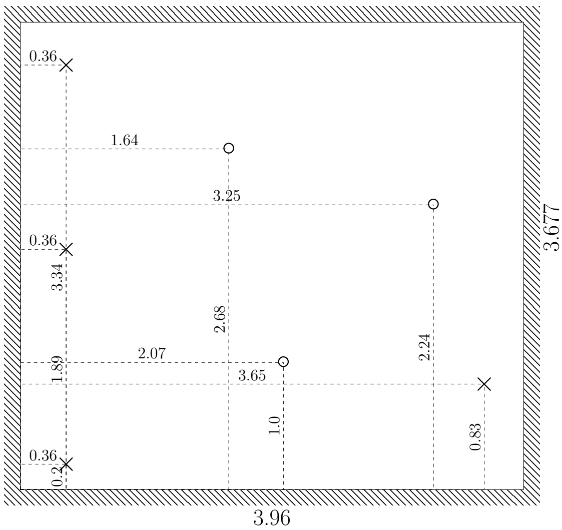
Frequency [Hz]	T60 [s] (N)	T30 [s] (N)	T20 [s] (N)
50	nan (0)	1.10 (4)	**0.84 (12)**
62	nan (0)	**0.57 (12)**	0.56 (12)
79	nan (0)	0.67 (12)	**0.40 (12)**
99	nan (0)	0.48 (12)	**0.48 (12)**
125	1.07 (9)	**0.48 (12)**	0.46 (12)
157	0.64 (12)	**0.52 (12)**	0.51 (12)
198	0.90 (12)	0.58 (12)	**0.59 (12)**
250	0.73 (12)	**0.60 (12)**	0.60 (12)
315	**0.62 (12)**	0.60 (12)	0.61 (12)
397	0.79 (12)	0.65 (12)	**0.66 (12)**
500	0.70 (12)	0.62 (12)	**0.64 (12)**
630	**0.71 (12)**	0.65 (12)	0.65 (12)
794	0.76 (12)	**0.64 (12)**	0.63 (12)
1000	**0.69 (12)**	0.64 (12)	0.64 (12)
1260	**0.70 (12)**	0.66 (12)	0.66 (12)
1587	**0.70 (12)**	0.68 (12)	0.68 (12)
2000	**0.70 (12)**	0.69 (12)	0.69 (12)
2520	**0.68 (12)**	0.67 (12)	0.66 (12)
3175	**0.68 (12)**	0.67 (12)	0.67 (12)
4000	**0.66 (12)**	0.64 (12)	0.63 (12)
5040	**0.61 (12)**	0.60 (12)	0.59 (12)
6350	**0.57 (12)**	0.55 (12)	0.55 (12)
8000	0.53 (9)	**0.50 (12)**	0.50 (12)



Room

- Room dimensions:
  - Length: 3.96 [m]
  - Width: 3.68 [m]
  - Height: 2.57 [m]
- Room volume: 37.42 [m^3]
- Temperature: 23.0 Celcius, Humidity: 35.0 %
- 12 combinations using 3 microphone (×) and 4 source positions (○):

Positions	X [m]	Y [m]	Z [m]
Microphone 1	1.64	2.68	1.44
Microphone 2	3.25	2.24	1.50
Microphone 3	2.07	1.00	1.82
Source 1	3.65	0.83	1.82
Source 2	0.36	1.89	1.40
Source 3	0.36	0.20	1.80
Source 4	0.36	3.34	1.40



F | Acceptance Test

The following appendix list all requirements stated in chapter 3. The requirements are listed with unique identifying number matching the number stated in chapter 3. Each requirement reference to a section in section F.1 explaining the validation of said requirement. The requirements have three different result options:

- ✓ if the requirement is fulfilled.
- (✓) if the requirement is partly fulfilled.
- × if the requirements is not fulfilled.

Req no.	**Requirement**	**Reference (Section)**	**Result**
1	Use equipment complying with at least IEC 61672-1 class 1 specifications seen in table 3.1	F.1.1	✓
2	The system must be calibrated using IEC 60942 class 1 calibrators, calibrating with a tolerance of ± 0.3 dB	F.1.2	✓
3	The equipment and calibration values must be documented with calibration dates, internal and serial reference number.	F.1.3	✓
4	The impulse must be calculated using linear deconvolution.	F.1.4	✓
5	The stimuli must cover all fractional-octave bands of interest, having a pink spectrum in each bands entire 3 dB bandwidth.	F.1.5	✓
6	The stimuli must have constant envelope within the range with the tolerance of the chosen sound card.	F.1.6	✓
7	Have an omni-directional source with a directivity with a maximum deviation as stated in table 3.2 and a frequency response of 100-5000 Hz	F.1.7	✓
8	Produce sound pressure levels at or above 90 dB(A).	F.1.8	✓
9	All fractional octave filter used for evaluation of decay curves must be IEC 61260 class 1 compliant.	F.1.9	✓
10	Conform with the documentation required in ISO 3382-2.	F.1.10	(✓)

Table F.1: Acceptance test.

F.1 | Requirement validation

The following subsections explains the fulfillment of each requirement. Each main requirement will account for any potential sub requirements stated in table F.1.

F.1.1 Use equipment complying with at least IEC 61672-1 class 1 specifications

The building regulations (BR15) states that, for acoustic measurements, the tolerance on equipment must not be larger than a specific amount. Specifically the requirements must comply with IEC 61672-1 class 1, stating that the frequency response of the equipment must not have tolerances higher than what is stated in table F.2.

Frequency [kHz]	0.25 to 1	>1 to 2	>2 to 4	>4 to 8	>8 to 12.5
Tolerances [dB]	1.0	1.0	1.5	2.5	4.0

Table F.2: IEC 61672-1 class 1 magnitude tolerance requirements [IEC 61672-1, 2014].

To meet the requirements all microphones are selected to be G.R.A.S. 40AD coupled with G.R.A.S. 26CA Preamplifier. The microphones are specified with a tolerance of ± 1 dB until 7.5 kHz, beyond 7.5 kHz they are specified with ±2 dB [G.R.A.S., 2018]. Since the microphones are build complying with IEC 61094-4 [IEC 61094-4, 1995], it is assumed that the tolerances mentioned in the datasheet comply with IEC 61672-1 Class 1 requirement. The 26CA is also accepted, as it is specified with ± 0.1 dB within 2.5 Hz - 200 kHz [G.R.A.S., 2010].

The device used for the actual recordings is an RME Fireface UCX II USB sound card. The Fireface sound card specifies a linear frequency response from 5 Hz to 20.8 kHz $\pm 0.1 dB$ @ 44.1 kHz with an SNR of 113 dB [RME, 2017], which is well within IEC 61672-1 class 1 requirements.

F.1.2 The equipment must be calibrated using IEC 60942 class 1 calibrators, calibrating with a tolerance of ± 0.3 dB

The entire system is calibrated using an Bruel and Kjær Type 4231 Sound Calibrator. The Type 4231 is specified to provide 94 dB @ 1kHz in accordance with IEC 60942 class 1 requirements having only 0.1 dB tolerance.

With the equipment stated above, the requirement for complying with building regulations (BR15) is accepted.

F.1.3 The equipment and calibration values must be documented with calibration dates, internal and serial reference number

The BAMPI program records all calibration values and saves the date for the calibration in a designated workspace for future reference if needed. All equipment is also saved into a configuration file which is saved alongside the measurement. The configuration file contains information about the device, device serial no. and internal reference number. A documentation report displays all required values in a sensible way which is easy for a user to look through. An example of such measurement report can be seen in appendix D.

F.1.4 The impulse must be calculated using linear deconvolution

The room impulse is to be calculated using linear deconvolution. This has been implemented in the BAMPI system, a flowchart of the process and elaboration of it can be found in appendix C under subsection B.12.1.

The stimuli used is a pink sweep. The sweep is designed in frequency [Müller and Massarani, 2001], reducing artifacts from synthesis in time. The signal is designed to have constant envelope in the frequency range of interest. The sweep used for measuring can be seen on figure F.1.

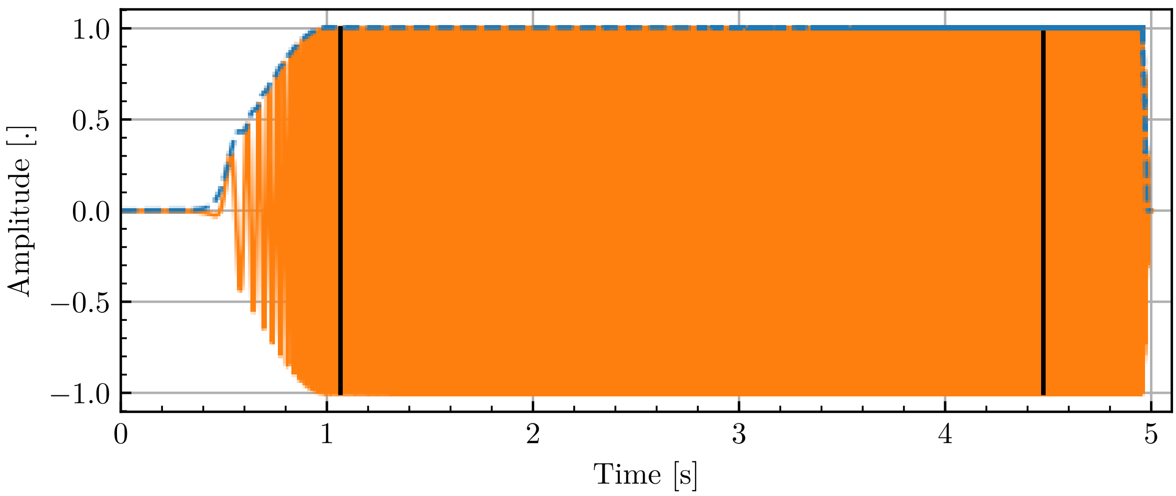


Figure F.1: The stimuli used for measurements, where (●) is the sweep, (●) is the envelope and (●) is the frequency area of interest.

F.1.5 The stimuli must cover all fractional-octave bands of interest, having a pink spectrum in each bands entire 3 dB bandwidth

The sweep is designed to be pink within 50 Hz to 12 kHz covering the loudspeakers entire frequency range. The spectral content of the sweep can be seen on figure F.2.

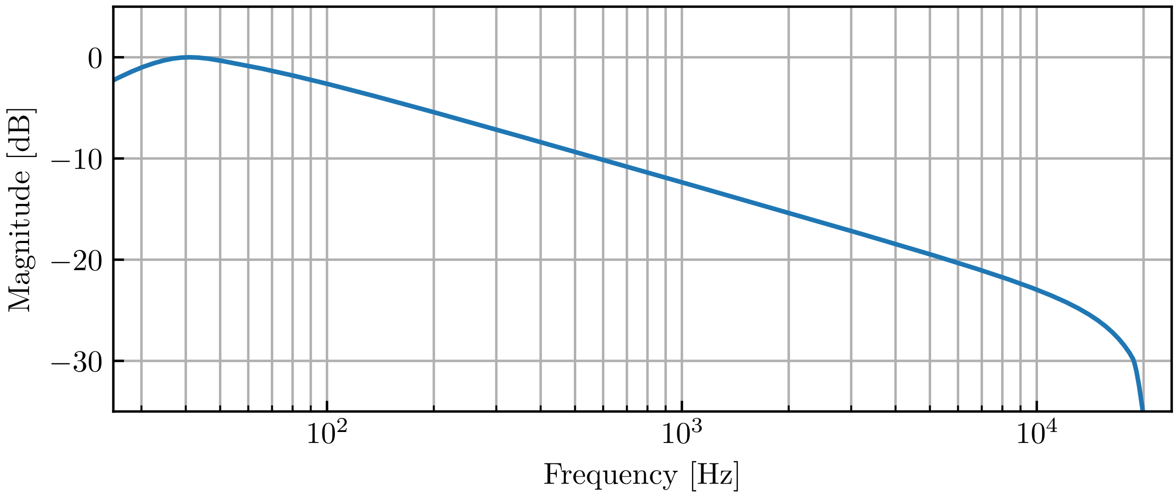


Figure F.2: Magnitude response of the stimuli used

F.1.6 The stimuli must have constant envelope within the desired frequency range with the tolerance of the chosen sound card.

The envelope of the stimuli is determined using the Hilbert transform. As seen on figure F.3 the envelope lies within 0.05 dB, which is lower than the 0.1 dB stated in the requirements and the envelope can be assumed constant in the frequency range of interest.

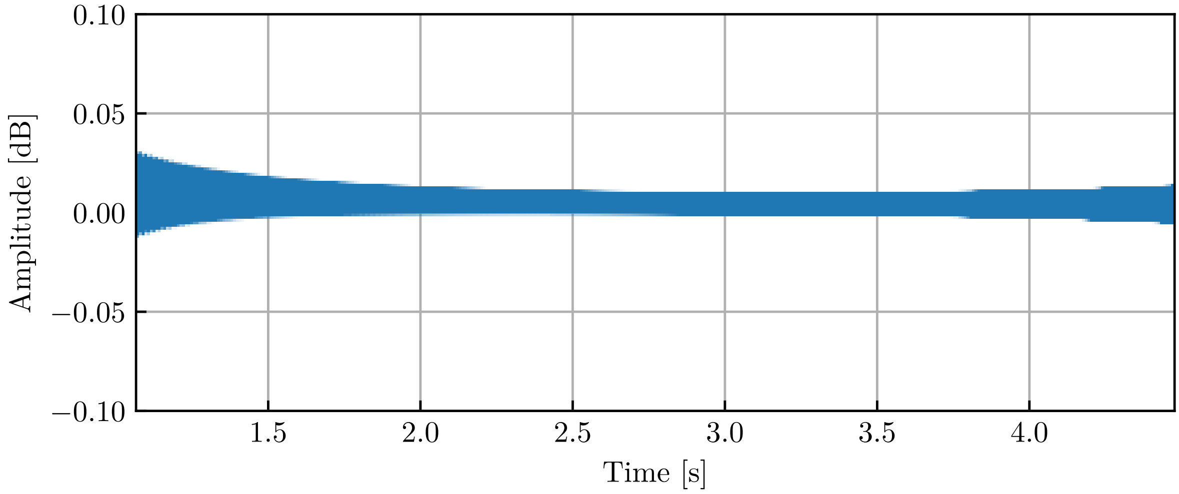


Figure F.3: The envelope of the signal used acquired using the Hilbert transform.

The stimuli and calculation procedure follows the guidelines of ISO 18233 and the requirement is accepted.

F.1.7 Have an omni-directional source with a directivity with a maximum deviation as stated in table 3.2 and a frequency response of 100-5000 Hz

Specific requirements for the loudspeaker are stated in ISO 3382-1 in order to perform a precision method measurement. In terms, the loudspeaker must be omnidirectional complying with the requirements listed in table F.3 and cover a frequency range of 100-5000 Hz. To uphold these requirement it is selected to use a Brüel and Kjær OmniPower loudspeaker. During the first week of measurement it was possible to use a Type 4292-L which was a lightweight version[Kjær, 2013], this was however changed to an older Type 4296 version [Kjær, 2008]. Both speakers uphold the directivity requirement.

Frequency [Hz]	125	250	500	1000	2000	4000
Maximum Deviation [dB]	± 1	± 1	± 1	± 3	± 5	± 6

Table F.3: Maximum deviation of directivity of source in decibels for excitation with octave bands of pink noise and measured in free field [ISO 3382-1, 2009].

F.1.8 Produce sound pressure levels at or above 90 dB(A)

The 6 Ohm 4292-L and 4296 is showcased in Bruel and Kjær manuals with a capability of playing 122 dB SPL using a 330 Watt amplifier. At the time of measuring, a mono channel 150 Watt IcePower amplifier module was available. Relying only on manufacturer specified wattage, the use of an 150 watt instead of 330 watt, will reduce the maximum sound pressure level by approximately 3.5 dB, allowing for 118 dB SPL. At 118 dB the potential sound pressure is still high above the required 90 dB(A).

F.1.9 All fractional octave filter used for evaluation of decay curves must be IEC 61260 class 1 compliant

All the fractional octave-band filters used in the measurements have all been generated using the same identical code, only with the center frequency being changed for each filter. Figure F.4 shows a normalized version of the filters used along with a class 0 requirement mask from IEC 61260-1 [IEC 61260-1, 2014]. The filter response is within the given tolerances and is accepted as IEC 61260-1 class 0 compliant.

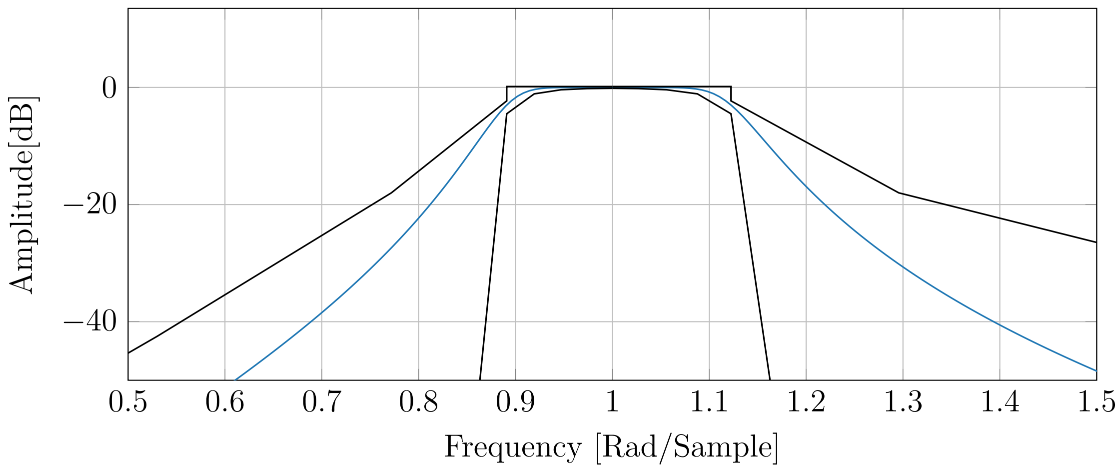


Figure F.4: Normalized $\frac{1}{3}$-octave filter (●) and IEC 61260-1 class 0 requirement mask (●)[IEC 61260-1, 2014].

F.1.10 Conform with the documentation required in ISO 3382-2

The measurement system only partly fulfill the required documentation as stated in ISO 3382-2. To be fully accepted the calculation method must be stated, more specifically how the averaging of values was done, either averaging impulses or reverberation times. Furthermore a display of all computed least-squares fit from the decay curves is missing, it only shows the most critical and least linear fits [ISO 3382-2, 2008]. The averaging method was not documented in each individual measurement report but only mentioned in subsection B.13.1.

G | Electrical Validation of Measurement System

G.1 | Purpose

To validate that the measurement system is measuring correctly, an electrical validation is performed to ensure that the voltage measured on both input and outputs is correctly interpreted.

G.2 | Method

This section describes the different methods used in the set-up and in measurements.

G.2.1 Calibration

The calibration procedure was handled by the BAMPI interface, with the user only specifying either record time or frequency of interest. The procedure used for calibration by the BAMPI program is documented in Appendix B.3.

Inputs

The inputs was not calibrated during these measurements, but loaded from a workspace. Detailed calibration information is noted in section G.3.2.

Outputs

The outputs was not calibrated during these measurements, but loaded from a workspace. Detailed calibration information is noted in section G.3.2.

Using Golden Device

For electrical validation a known device is used as "Device-Under-test (DUT)". A Brüel & Kjear Type 1617 band pass filter is used as DUT. The Type 1617 is set to provide a C weighting filter, which is to be measured. The type 1617 device is measured using a National Instruments NI-4461 Data acquisition card for reference.

G.3 | Equipment and Settings

This section contains all equipment used for performing the measurements. Table G.1 lists the equipment used.

G.3.1 Equipment List

Item no.	Description/Name	Serial no.	Internal reference no.
1	Computer	NaN	NaN
2	Fireface UCX	23815212	AAU108246
3	B&O ICEPOWER custom amplifier	00003	NaN
4	Brüel & Kjaer Type 1617	1396255	AAU08455-00
5	Digilent Analog Discovery 2	DA2A9BA	AAU2179-10
6	National Instruments NI-4461	Not Stated	AAU64640

Table G.1: List of equipment.

G.3.2 Settings

This section contains all settings chosen for the performed measurements.

Bold dates	describes denotes a value calibrated during the measurement.
Regular date	denotes a value loaded from a workspace file with defined calibration values.
Italic Dates	describes a value that has been manually altered by a user.

Sound card and Computer

The sound card is configured with the following settings:

Samplerate	48000
Buffer size	1024
Driver	ASIO

The measurements were performed on a computer with Windows 7 and version 1.0.0 of BAMPI. By selecting ASIO driver it is ensured that any additional audio driver installed does not intefere with recordings or playback [Steinberg, 2017]. The Buffer size is set to 1024.

Input and Output Sensitivity

Table G.2 denotes the calibration values used during the measurements.

Input no.	Gain $\frac{Number}{volt}$ [dB]	Calibration Date
1	-11.35	24/4/2018
2	-11.35	24/4/2018
5	-19,82	24/4/2018

(a) Input sensitivity.

Output no.	Gain $\frac{volt}{number}$ [dB]	Calibration Date
1	19.40	24/4/2018

(b) Output sensitivity.

Table G.2: Input and Output gains with the respective sensitivity and date of calibration.

Amplifier

The amplifier are attached to ensure that the conditions during the electrical validation are identical to the measurement situation it is to be used in. Preliminary measurement using different amplifiers have shown 50 Hz artifacts in the measurements. The amplifier is left disconnected to the loudspeaker but connected to the measurement chain with the power on. Table G.3 denotes the amplifier used during the measurements. The amplifiers gain value is noted from their respective data sheet.

Item no.	Name	Channel location	Gain [dBV]
3	B&O ICEPOWER custom amplifier	1	30.00

Table G.3: The amplifier for both output used with its respective gain and channel location

G.3.3 Data acquisition card

The National Instruments NI-4461 sweeps the filter using a stepped sine with logarithmic spacing with the following settings:

Samplerate	48000
Generator amplitude	1 [V]
Settle time	0.025 [s]
Settle cycles	5
Integration time	0.025 [s]
Integration cycles	5

G.4 | Peripheral Connections

This section describes the different connections to the sound card and all the peripherals used. It should be noted that the wirings on figure G.1 is not noted with the specific type of cable used.

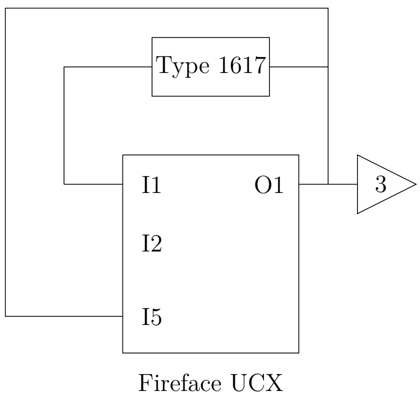


Figure G.1: Schematic of the sound card and all connected periperals.

Output channel 1 is connected to input channel 5 and is used as reference signal to generate the impulse response

G.5 | Measurements

Table G.4 denotes the gains settings applied by the user during the measurements.

Output Channel	Gain Setting [dB]
1	0.0

Table G.4: Gain values specified by user.

G.5.1 BAMPI

The BAMPI program performs a linear deconvolution using a logarithmic sweep, deconvolving with a recorded version of said sweep. By doing so any delay and characteristics introduced by the sound card is removed. All recordings can be found in file `Data/Measurements.mat`. Both channel 1 and 2 was used in two separate measurements. Only the magnitude response is compared since the national instrument card does not provide a continuous time signal, to generating an impulse response, only discrete magnitude and phase values.

Stimuli

Both channels were subjected to the following stimuli on their respective channel. All sweeps are synthesized in frequency [Müller and Massarani, 2001]

- Channel 1: Settings for Stimuli: Sweep - Type: Log - Time: 3.0 - Frequency Range: 5.0-20000.0, Degree of Linearty: 99.84 Zero padding before 0.5 [s], after 0.5 [s]

Analysis of Channel 1

The magnitude response of the recorded impulse from channel 1 is shown on figure G.2.

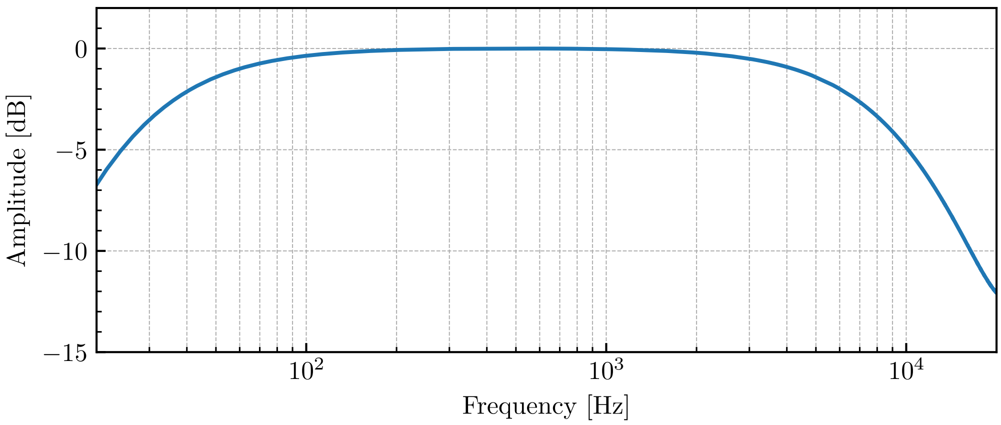


Figure G.2: Single sided magnitude response (N = 192000 [.])

The characteristics of a type C weighting filter clearly shows.

Analysis of Channel 2

The magnitude response of the recorded impulse from channel 2 is shown on figure G.3.

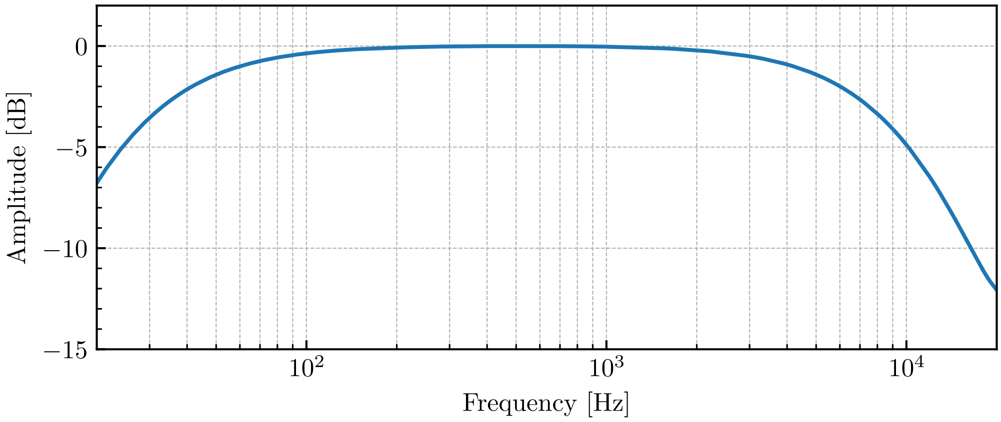


Figure G.3: Single sided magnitude response (N = 192000 [.])

The characteristics of a type C weighting filter clearly shows.

G.5.2 National Instruments

The national instruments card only had one channel for making a network analysis, since the second was reserved for a reference signal. The recorded signal can be found at `CfilterBKTYPE1617.txt`

Stimuli

As stated in the settings section a stepped sine measurement was performed with the prescribed settings.

Analysis of measurement

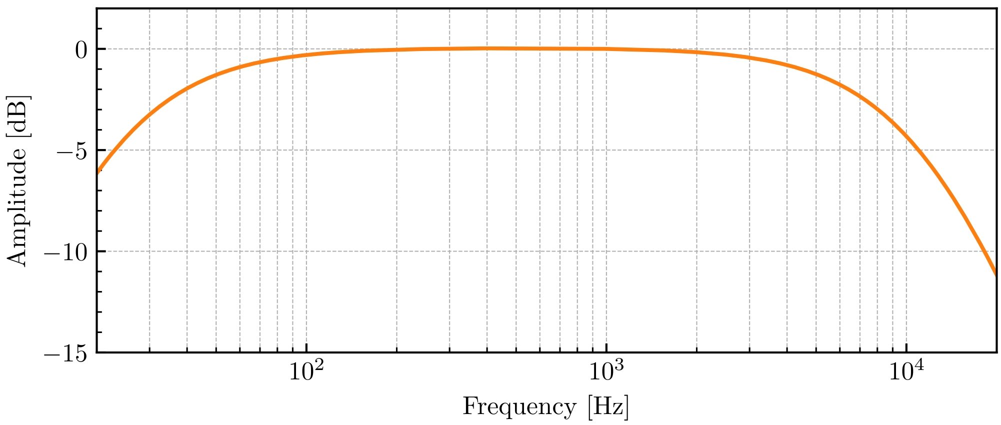


Figure G.4: Single sided magnitude response (N = 192000 [.])

G.6 | Comparison

On figure G.5 the two measurements are compared. The difference between each response are not shown due to the bin-by-bin frequency resolution is not identical.

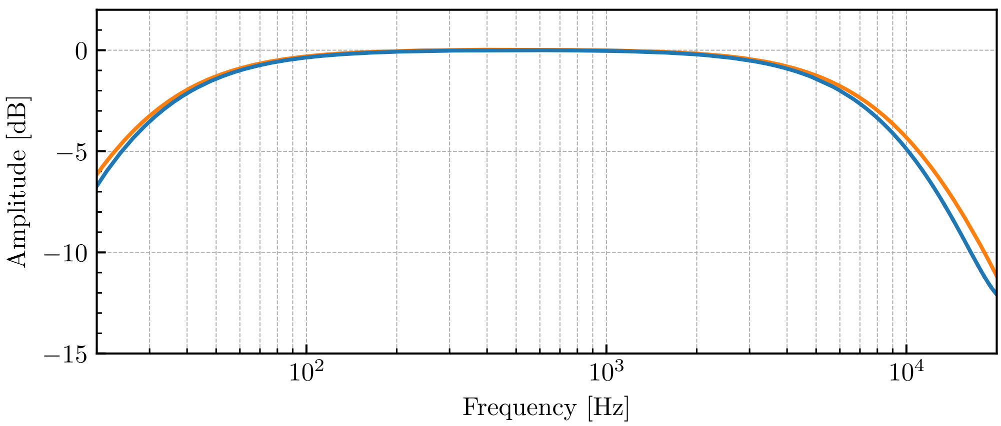


Figure G.5: Comparison of Magnitude response of C weighting filter between National Instrument (●) and RME Fireface UCX (●)

The two responses show slight deviations between each other.

G.7 | Tolerances

The following table shows the tolerances of all noted equipment used for performing measurements.

Item no.	Name	Tolerance [dB]	Frequency Range [Hz]
2	Fireface UCX	0.0 - 0.5	6 - 20.600
5	Digilent Analog Discovery 2	0.05 - 0.05	0 - 1.000.000
6	National Instruments NI-4461	0.003 - 0.003	20 - 20.000

Table G.5: All input peripherals used for performing measurements with their respective tolerances in the stated frequency area.

G.8 | Error

No errors was noted during the electrical validation.

G.9 | Raw Data

All raw data paths mentioned above is enclosed in CD and is structured as shown in figure G.6.

- Electrical Validation
  - Data
    - Impulses.mat
    - Measurements.mat
  - Settings
    - GainSettings.mat
    - TemplateSettings.ini
    - Workspace.ini
  - C filter BK TYPE 1617.txt

Figure G.6: File structure of a saved measurement.

G.10 | Conclusion

The same type C weighting filter has been measured with two different measurement systems. The responses show slight deviation from each other at low and high frequencies. This is related to the impedance between each card not being identical alongside with an increasing tolerance at these specific areas. The electric validation is accepted based on the responses being adequately accurate considering the tolerances within the deviating frequency range.

H | Acoustical Validation of Measurement System

H.1 | Purpose

To ensure that the measurement system is calculating and evaluating the recordings properly, an acoustical validation is required. The acoustical validation ensures the the entire system is capable of performing calibrated acoustic measurements and calculating impulse response and reverberation times correctly.

H.2 | Method

This section describes the different methods used throughout the set up and measurements.

H.2.1 Calibration

The calibration procedure was handled by the BAMPI interface, with the user only specifying either record time or frequency of interest. The procedure used for calibration by the BAMPI program is documented in Appendix B.3.

Inputs

The inputs was not calibrated during these measurements, but loaded from a workspace. Detailed calibration information is noted in section H.3.2.

Outputs

The outputs was not calibrated during these measurements, but loaded from a workspace. Detailed calibration information is noted in section H.3.2.

Direct comparison

To ensure that the BAMPI measurement system is performing correct calculations a direct comparison with an "All-in-one" Brüel and Kjær Type 2270 Handheld analyzer is performed. The Type 2270 can provide stimuli and perform calculation of T20 and T30 reverberation times based on the interrupted noise method [ISO 3382-2, 2008]. Both systems will perform measurement in a designated and controlled room using the same loudspeaker and amplifier. Both systems will be using the same microphone positions. Both interrupted noise method and squared impulse response method for BAMPI will be done.

Indirect comparison

To eliminate the measurement procedure and focusing only on the value calculations involved in determining the reverberation time an already determined impulse will be used and fed to the system. A large survey has been done with a specific recorded impulse which is to be used [Katz, 2004]. Using this specific impulse makes the results comparable with a wide range of software used for determining reverberation times.

H.3 | Equipment and Settings

Table H.1 lists the equipment used for performing the measurements.

H.3.1 Equipment List

Item no.	Description/Name	Serial no.	Internal reference no.
1	Computer	NaN	NaN
2	Fireface UCX	Not stated	Not stated
3	B&O ICEPOWER custom amplifier	00003	NaN
4	Beyerdynamic DT770	NaN	AAU203718
5	Brüel & Kjær Type 2270	XX	XX
6	Brüel Kjaer Omni Power Type 4292-L	2251009	AAU33950
7	KM 8004	3693	AAU33192
8	RME Micstasy	23694218	AAU86849
9	G.R.A.S 46AD	321880	AAU1111
10	G.R.A.S 26CA	277020	AAU846512
11	G.R.A.S 26CA	277293	AAU652147
12	G.R.A.S 46AD	321882	AAU31564
13	G.R.A.S 26CA	277294	AAU88855
14	G.R.A.S 26CA	277019	AAU11254
15	G.R.A.S 40AD	252648	AAU846423
16	G.R.A.S 40AD	60568	AAU975632
17	G.R.A.S 40AD	73551	AAU99756
18	G.R.A.S 40AD	252624	AAU77231
19	Brüel Kjaer Acoustical Calibrator Type 4231	2115338	AAU33691
20	Analog Discovery 2	DA2A9BA	217310
21	Leica Disto D2	258963	AAU2157-64

Table H.1: List of equipment.

H.3.2 Settings

This section contains all settings chosen for the performed measurements.

Bold dates	describes denotes a value calibrated during the measurement.
Regular date	denotes a value loaded from a workspace file with defined calibration values.
Italic Dates	describes a value that has been manually altered by a user.

Sound card and Computer

The sound card is configured with the following settings:

Samplerate	48000
Buffer size	1024
Driver	ASIO

The measurements were performed on a computer with Windows 7 and version 1.0.0 of BAMPI. By selecting ASIO driver it is ensured that any additional audio driver installed does not interfere with recordings or playback [Steinberg, 2017]. The Buffer size is set to 1024.

Input and Output Sensitivity

Table H.2 denotes the calibration values used during the measurements.

Input no.	Gain $\frac{Number}{volt}$ [dB]	Date of Calibration
11	-22.90	5/4/2018
12	-22.93	5/4/2018
13	-22.96	5/4/2018
14	-22.99	5/4/2018
15	-23.04	6/4/2018
16	-22.87	6/4/2018
17	-22.46	24/4/2018

(a) Input sensitivity.

Output no.	Gain $\frac{volt}{number}$ [dB]	Date of Calibration
1	19.40	6/4/2018
7	19.66	24/4/2018
8	19.63	24/4/2018

(b) Output sensitivity.

Table H.2: Input and output gains with the respective sensitivity and date of calibration.

Microphones

Table H.3 denotes all the microphones used during the measurements. The microphones are calibrated using item 19 on the equipment list.

Item no.	Name	Channel location	Sensitivity $[\frac{mV}{Pa}]$	Date of calibration
9	G.R.A.S 46AD	11	47.90	6/4/2018
12	G.R.A.S 46AD	14	45.50	6/4/2018
15	G.R.A.S 40AD	12	49.60	6/4/2018
16	G.R.A.S 40AD	13	42.70	6/4/2018
17	G.R.A.S 40AD	15	51.10	6/4/2018
18	G.R.A.S 40AD	16	49.60	6/4/2018

Table H.3: All microphones used with their respective sensitivity, channel location and calibration date.

Amplifiers

Table H.4 denotes all the amplifiers used during the measurements. The amplifiers gain value are noted from their respective data sheet.

Item no.	Name	Channel location	Gain $[dBV]$
3	B&O ICEPOWER custom amplifier	1	30
8	RME Micstasy	11	0.00
8	RME Micstasy	12	0.00
8	RME Micstasy	13	0.00
8	RME Micstasy	14	0.00
8	RME Micstasy	15	0.00
8	RME Micstasy	16	0.00
10	G.R.A.S 26CA	12	-0.30
11	G.R.A.S 26CA	13	-0.30
13	G.R.A.S 26CA	15	-0.30
14	G.R.A.S 26CA	16	-0.30

Table H.4: All amplifiers for both input and output used along with their respective gain and channel location

Transducers

Table H.4 denotes all the transducers used during the measurements. The transducers sensitivity value are noted from their respective datasheet and is only used for estimations during the actual measurement.

Item no.	Name	Channel location	Sensitivity
4	Beyerdynamic DT770	7	96.00 [dB SPL/mW]
6	Brüel Kjaer Omni Power Type 4292-L	1	88.00 [dB SPL/W/m]

Table H.5: All loudspeakers and headphones with their respective sensitivity and channel location.

Additional Equipment

Table H.6 denotes all additional equipment used during the measurements.

Item no.	Name	Settings/Comments
19	Brüel Kjaer Acoustical Calibrator Type 4231	Used to calibrate all microphones.
20	Analog Discovery 2	Used to calibrate sound cards
21	Leica Disto D2	Used to measure room and positions
22	KM 8004	Used to measure temperature and humidity

Table H.6: All additional equipment which is not visible on figure H.1.

H.4 | Peripheral Connections

This section describes the different connections to the sound card and all the peripherals used. It should be noted that the wirings on figure H.1 is not noted with the specific type of cable used.

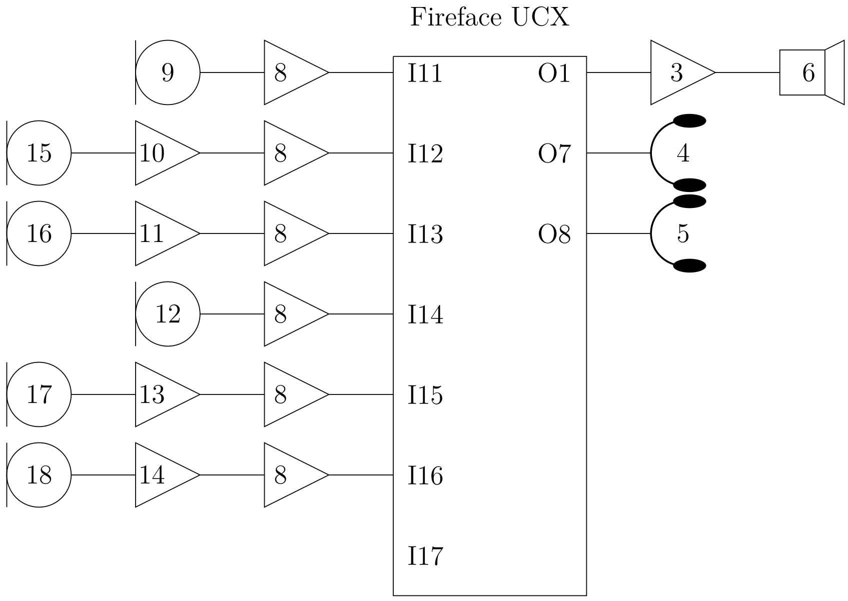
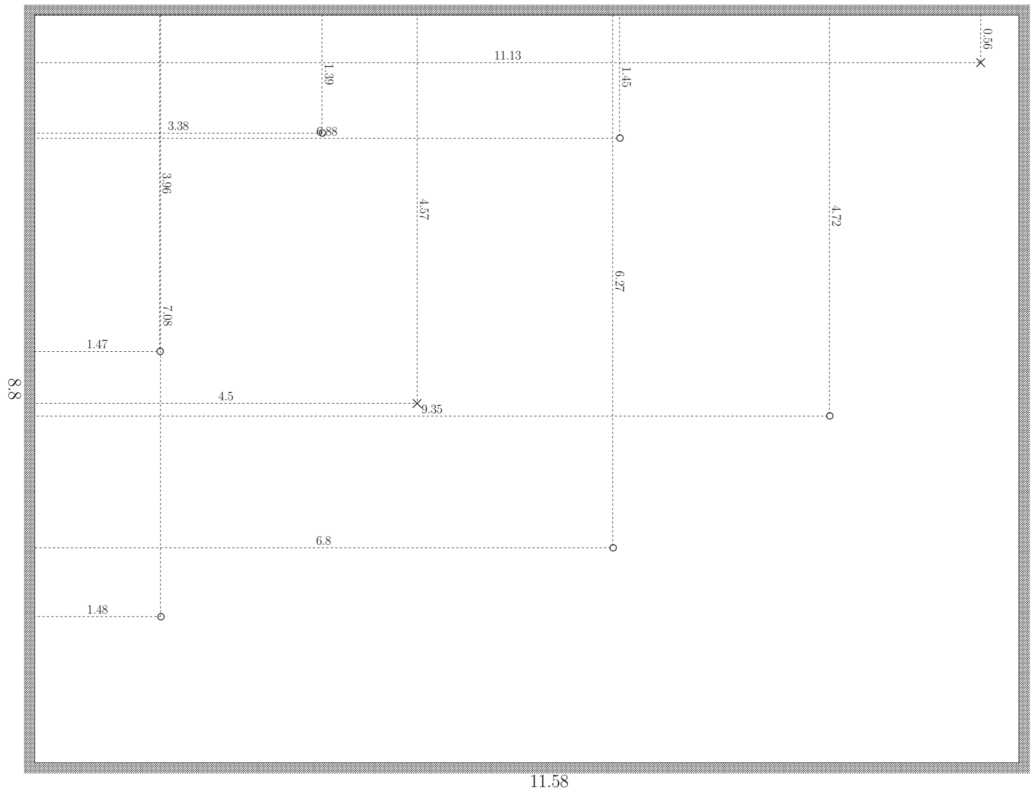


Figure H.1: Schematic of the sound card and all connected peripherals.

Output channel 1 is connected to input channel 17 and is used as reference signal.

H.4.1 Microphone and Source Position

During the measurements, the following microphone and amplifier positions have been used.



(a) Graphical representation of microphone and source positions. The room height is 2.88m.

Positions	Y [m]	X [m]	Z [m]
Microphone 1	1.45	6.88	1.49
Microphone 2	4.72	9.35	1.50
Microphone 3	6.27	6.80	1.50
Microphone 4	7.08	1.48	1.48
Microphone 5	3.96	1.47	1.50
Microphone 6	1.39	3.38	1.50
Source 1	1.39	3.38	1.50
Source 2	1.39	3.38	1.50

(b) List of microphone and loudspeaker positions.

Figure H.2: All distances are noted in meters. Sources are noted × and microphones ○.

H.5 | Measurements

36 recording combinations have been conducted with both Brüel and Kjær Type 2270 and BAMPI. All measurements were done with an ambient temperature of 22 degrees celcius and 31 % humidity. During measurement 1, pink noise was used on channel 1 in the duration of

5 seconds with an extra 1 second zero padding in the end to capture the decay. For each measurement the noise was synthesized again to ensure new noise for each measurement. Both systems were adjusted prior to the measurement to provide an equal amount of sound pressure level. The following filter settings was applied to the input and output channels:

Filter Settings (Inputs)

- Channel 11: Filter Settings: LP: Passband 0.1 [dB] @ 12445.0 [Hz], Stopband 20.0 [dB] @ 16000.0 [Hz], HP Passband 0.1 [dB] @ 40.0 [Hz], Stopband 20.0 [dB] @ 31.0 [Hz]
- Channel 12: Filter Settings: LP: Passband 0.1 [dB] @ 12445.0 [Hz], Stopband 20.0 [dB] @ 16000.0 [Hz], HP Passband 0.1 [dB] @ 40.0 [Hz], Stopband 20.0 [dB] @ 31.0 [Hz]
- Channel 13: Filter Settings: LP: Passband 0.1 [dB] @ 12445.0 [Hz], Stopband 20.0 [dB] @ 16000.0 [Hz], HP Passband 0.1 [dB] @ 40.0 [Hz], Stopband 20.0 [dB] @ 31.0 [Hz]
- Channel 14: Filter Settings: LP: Passband 0.1 [dB] @ 12445.0 [Hz], Stopband 20.0 [dB] @ 16000.0 [Hz], HP Passband 0.1 [dB] @ 40.0 [Hz], Stopband 20.0 [dB] @ 31.0 [Hz]
- Channel 15: Filter Settings: LP: Passband 0.1 [dB] @ 12445.0 [Hz], Stopband 20.0 [dB] @ 16000.0 [Hz], HP Passband 0.1 [dB] @ 40.0 [Hz], Stopband 20.0 [dB] @ 31.0 [Hz]
- Channel 16: Filter Settings: LP: Passband 0.1 [dB] @ 12445.0 [Hz], Stopband 20.0 [dB] @ 16000.0 [Hz], HP Passband 0.1 [dB] @ 40.0 [Hz], Stopband 20.0 [dB] @ 31.0 [Hz]

Filter Settings (Outputs)

- Channel 1: Filter Settings: LP: Passband 0.1 [dB] @ 12445.0 [Hz], Stopband 20.0 [dB] @ 16000.0 [Hz], HP Passband 0.1 [dB] @ 40.0 [Hz], Stopband 20.0 [dB] @ 31.0 [Hz]
- Channel 8: Filter Settings: LP: Passband 0.1 [dB] @ 12445.0 [Hz], Stopband 20.0 [dB] @ 16000.0 [Hz], HP Passband 0.1 [dB] @ 40.0 [Hz], Stopband 20.0 [dB] @ 31.0 [Hz]

For simplicity each individual measurement results is not shown, they can be found in the folder `AcousticValidation`, located on the enclosed CD. The folder has the following structure:

- Seminarrum A4-106
  - 24-04-2018
    - BAMPI-file-Impulse
    - BAMPI-file-Noise
      - Data
        - Measurement.mat
      - Report.pdf
  - 30-04-2018

Within both "Impulse" and "Noise" a .pdf is available with measurement documentation and intermediate results displayed.

H.6 | Results

Before comparing each system to each other it is ensured that the two measurement method available in BAMPI with interrupted noise and integrated impulse responses are consistent within each other. A T-test has been conducted on a set of T20 values derived in BAMPI from both measurement methods. The results can be seen in table H.7 which clearly shows that all values in each band are identical. The measurements was performed the 24-04-2018 using the same measurement system and setup described throughout this chapter.

Band	p-value
63 Hz	0.83
125 Hz	0.42
250 Hz	0.44
500 Hz	0.79
1000 Hz	0.90
2000 Hz	0.84
4000 Hz	0.74
8000 Hz	0.78

Table H.7: T-test results from the distributions shown in figure H.3

H.6.1 Direct Comparison

The following shows histograms for each frequency band in $\frac{1}{1}$-octave band for comparison against the Brüel and Kjær Type 2270 Analyser.

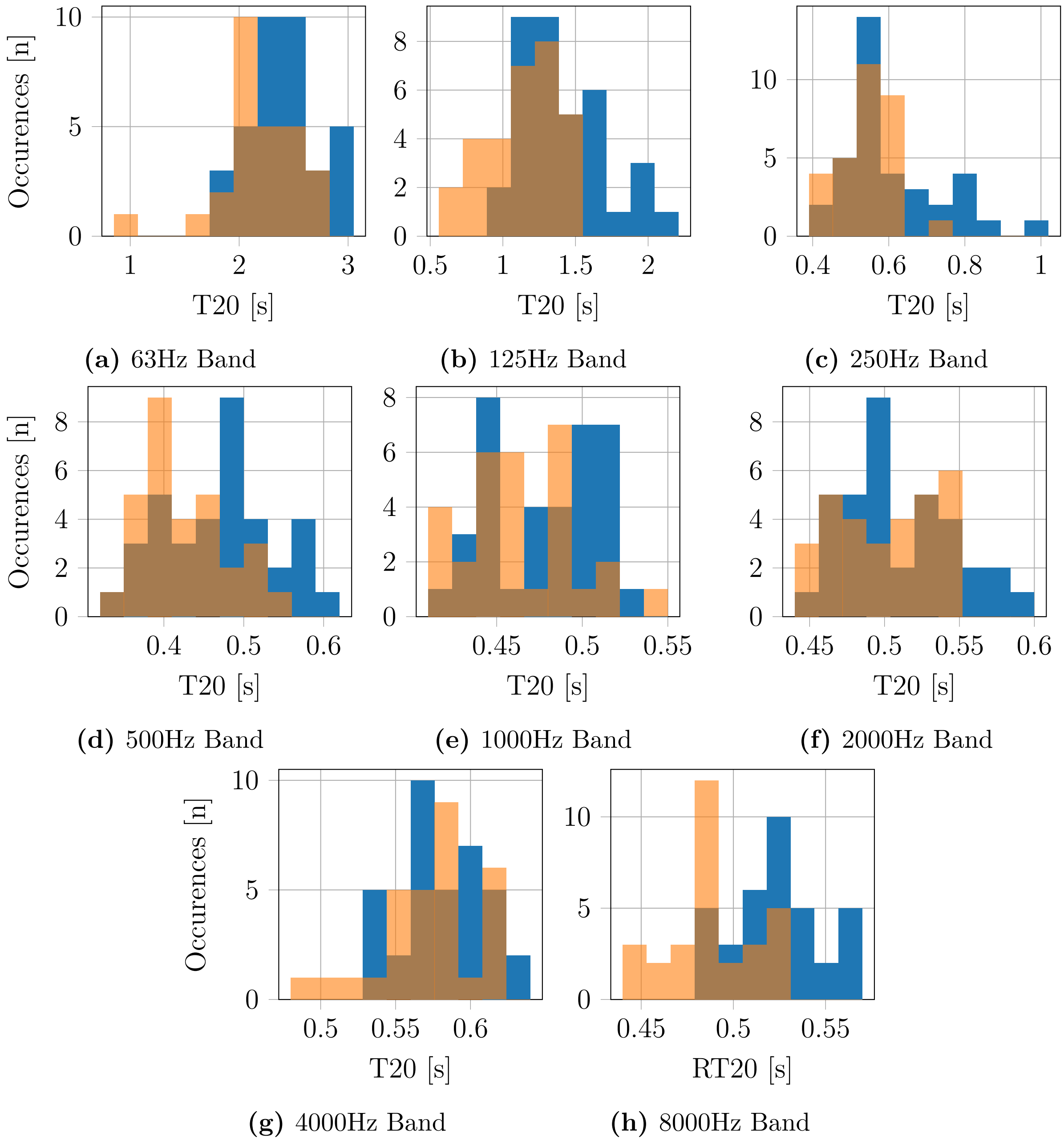


Figure H.3: Histogram of T20 times in $\frac{1}{1}$-Octave bands. BAMPI (●) and B&K Type 2270 (●)

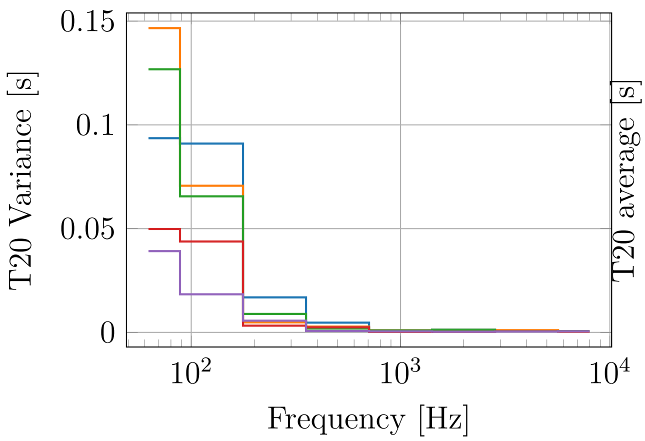
First measurement (24-05-2018) showed in post processing to be missing 6 measurement from the BAMPI program. A T-test is performed to achieve validation that the BAMPI program measures the same values as the Type 2270. The T-test assumes the samples to be normally distributed. When comparing the results in figure H.3 it clearly shows that the distributions are not normal yet and more data is required to achieve a normal distribution. The T-test is performed regardless of the distributions and the results can be shown in table.

Band	p-value
63 Hz	0.06
125 Hz	$0.05{\cdot}10^{-3}$
250 Hz	0.07
500 Hz	0.46
1000 Hz	0.05
2000 Hz	0.28
4000 Hz	$0.14{\cdot}10^{-2}$
8000 Hz	$2.98{\cdot}10^{-14}$

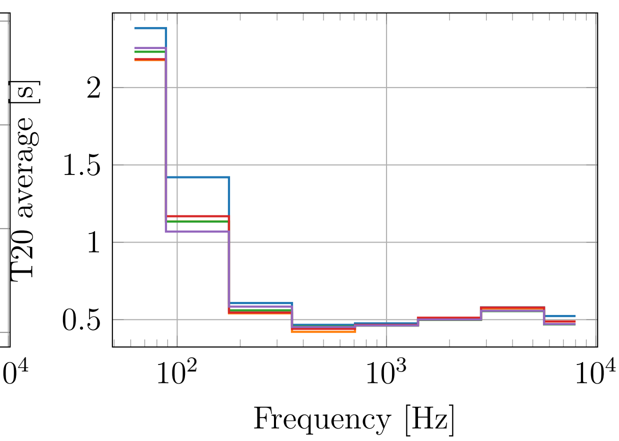
Table H.8: T-test results from the distributions shown in figure H.3

table H.8 shows that only 5 out of 8 bands are statistically identical. It should be noted that the data has not been sorted for outliers, they are analyzed as seen on figure figure H.3. Due to time constraints of the project no more data has been collected with the Type 2270.

For a more coherent overview of the results figure H.4 shows the variance and average of T20 values between BAMPI and the Type 2270 as a function of frequency. It should be noted that BAMPI was tested on two different days whereas B & K was only tested on the first of these two days.



(a) Variance within T20 values



(b) Average T20 values

Figure H.4: Comparison of means and variance. B&K Type 2270(●), BAMPI w. Interrupted noise (24/04) (●), BAMPI w. Interrupted noise (30/04)(●), BAMPI w. Integrated impulse (24/04) (●), BAMPI w. Integrated impulse (30/04) (●).

Figure H.4 shows that while the absolute values between the two devices are different in the lower frequencies, it clearly shows that the integrated impulse method displays much lower variance than the Type 2270.

H.6.2 Indirect Comparison

To eliminate the situation of comparing results with a device that may measure differently than the majority of sound analyzers, a calculation is performed on a recorded impulse used in an international round robin test [Katz, 2004]. The calculated T20 values can then be compared with 19 different institution, from nine different countries, using 25 different software packages. where 57% were consultants, 38% were research, and 5% were software development. The software used was 40% commercially available and 60% experimental.

While the statistical data from the survey was sparsely available, having only the median and standard deviation to rely on, a very important tendency showed. The BAMPI program calculated the T20 values for the 125 Hz band 0.55 seconds higher than the median value from the sample group. Comparing that result with figure H.4 it shows that the Type 2270 is measuring even higher.

Besides the lowest band of 125 Hz, where the value is high in the BAMPI program, the remaining bands are still within 0.02 seconds of the median value.

H.7 | Tolerances

The following tables shows the tolerances of all noted equipment used for performing measurements. Table H.9 is the input peripherals. Table H.10 is the output peripherals. Additional equipment from external equipment can be seen in table H.6.

Item no.	Name	Tolerance [dB]	Frequency Area [Hz]
8	RME Micstasy	+0.0/-0.1	20 - 100000
9	G.R.A.S 46AD	+1.0/-1.0	12.5 - 7500
10	G.R.A.S 26CA	+0.2/-0.2	2.5 - 200000
11	G.R.A.S 26CA	+0.2/-0.2	2.5 - 200000
12	G.R.A.S 46AD	+1.0/-1.0	12.5 - 7500
13	G.R.A.S 26CA	+0.2/-0.2	2.5 - 200000
14	G.R.A.S 26CA	+0.2/-0.2	2.5 - 200000
15	G.R.A.S 40AD	+1.0/-1.0	12.5 - 7500
16	G.R.A.S 40AD	+1.0/-1.0	12.5 - 7500
17	G.R.A.S 40AD	+1.0/-1.0	12.5 - 7500
18	G.R.A.S 40AD	+1.0/-1.0	12.5 - 7500

Table H.9: All input peripherals used for performing measurements with their respective tolerances in the stated frequency area.

Item no.	Name	Tolerance [dB]	Frequency Area [Hz]
3	B&O ICEPOWER custom amplifier	+0.5/-0.5	1.5 - 90000
4	Beyerdynamic DT770	+1.0/-1.0	5.0 - 35000
6	Brüel Kjaer Omni Power Type 4292-L	+1.0/-1.0	50.0 - 12000.0

Table H.10: All output peripherals used for performing measurements with their respective tolerances in the stated frequency area.

Item no.	Name	Tolerance	Unit of measurement
19	Brüel Kjaer Acoustical Calibrator Type 4231	+0.2/-0.2	[SPL]
20	Analog Discovery 2	+0.1/-0.1	[dBV]
21	Leica Disto D2	+1.0/-1.0	[mm]
22	KM 8004	+1.0/-1.0	[°Celsius]

Table H.11: All noted equipment not visible on figure H.1 tolerances and unit of measure.

H.8 | Error

6 Measurements using interrupted noise methods was not saved due to technical errors in measurement procedure.

During measurement the positioning of the the microphones were very susceptible to changes, as a change of only a few centimeters resulted in different results at the 8 kHz band.

It was furthermore not possible to acquire the raw measurement from the Type 2270 to validate the recorded signal.

H.9 | Conclusion

Without further investigation into achieving comparable measurements with the Bruel & Kjær Type 2270 the acoustic validation is accepted based on the results shown, where the results achieved in BAMPI are in the higher end of the sample group [Katz, 2004]. The histograms from figure H.3 also showed lack of being normally distributed and potentially having skewed distributions, ultimately resulting in a failed T-test [Boneau, 1960]. It is assumed that a successful t-test can be achieved if enough samples from the Type 2270 is collected. This is however not done due to time constraints.

I | Development of Questionnaire

The purpose of this chapter is to document the methodology behind the questionnaire and the segments of the finished questionnaire and. For the finished questionnaire in Danish refer to Appendix L and for the finished questionnaire in English refer to Appendix K.

Several questionnaires have been developed in recent years for socio-acoustic surveys, with examples such as COST TU0901 [Rasmussen and Machimbarrena, 2014a], or the REBUS project [Knudsen et al., 2017]. These however have mainly focused on noise annoyance, meaning no surveys have been made on the annoyance, disturbance or satisfaction of room acoustics in dwellings to the authors knowledge. The ISO 15666 [ISO 15666, 2003] also standardizes the method for assessment of noise annoyance. These works and standards will be used as inspiration in designing the questionnaire.

ISO 15666:2003 - Assessment of noise annoyance by means of social and socio-acoustic survey describes the method for questions to be asked, response scales and key aspects of conducting a socio-acoustic survey. [ISO 15666, 2003]

I.1 | Scope

The main purpose of the questionnaire is to acquire data from occupants which can be used to correlate subjective answers with objective room acoustical parameters described in section 2.3. The goals of the questionnaire are defined as:

- To acquire an acoustic description of the dwelling.
- To acquire the dwellings impact on the occupants speech intelligibility.
- To acquire the dwellings impact on noise sources residing inside the dwelling.

As mainly Danish occupants are going to participate in this survey the questions and answers in the questionnaire will be developed in Danish, as the native language should provide a better understanding of the questionnaire. However for the readability of this report the questionnaire has been translated into English.

I.2 | Methodology

The questionnaire should be written in as simple terms as possible to minimize errors in answers due to misunderstanding or not understanding the question or scale used. The words used should therefore both be understood by a 18 year old and a 90 year old. The ISO 15666 specifies the optimal wordings of the questions as:

Thinking about the last (12 months or so), when you are here at home how much does noise from (noise source) bother, disturb or annoy you? [ISO 15666, 2003]

When designing the questions for the questionnaire it is important to ask direct questions which names the specific situation or source and has a limited number of answerers. Compared to asking indirect open-ended questions as the answers are more difficult to analyze and not directly comparable.

Two types of scales are specified in ISO 15666. A verbal 5-point Likert scale as seen in table I.1 or a numerical 11-point scale from 0 - 10 as seen in table I.2. The advantage of the verbal 5-point scale is that it is has the clearest and most transparent communication due to choosing a verbal category [ISO 15666, 2003]. The disadvantage is that the interval of verbal categories are not necessarily equidistant to each other [Rasmussen and Machimbarrena, 2014a]. The categories from the standard are also backed up by [Rasmussen and Machimbarrena, 2014a] which conducted a study on the preferred words for each category, which showed the same exact words.

NOT AT ALL	SLIGHTLY	MODERATELY	VERY	EXTREMELY

Table I.1: Verbal 5-point scale as prescribed in [ISO 15666, 2003].

The advantage of the numerical 11-point scale is that it is a base-10 numeric system which most people are familiar with. This is also the reason the standards prefers a 11-point scale over a 5-point or 7-point. There is however arguments for only using a 7-point scale as scales with an increased number of scale points is not necessarily equal to an increased resolution [Ramsay, 1973] and can be more susceptible to noise. The disadvantage of a numerical scale without labels is that the respondent could have tendencies meaning comparing respondents answers can be difficult if they do interpret the scale the same. This response tendency can however be minimized using verbal labels as anchors in the scale. This is also known as a Borg scale [Pashler and Wixted, 2002]. The use of anchors can therefore both be an advantage and a disadvantage.

NOT AT ALL										EXTREMELY
0	1	2	3	4	5	6	7	8	9	10

Table I.2: Numerical 11-point scale as prescribed in [ISO 15666, 2003].

REBUS uses mostly 5-point verbal scales [Knudsen et al., 2017], while COST TU0901 uses the 11-point numerical scale. The reasoning for using these scale types are specified in COST TU0901 in order to conform with ISO 15666 while it is assumed that the reason is the same for REBUS for most of it scales. It is chosen to use a numerical 11-point scale as this scale should results in the best interval data. It was considered using the verbal anchors from the 5-point Likert scale, this was however dropped as the standard does not use this. To reduce the scale size the endpoint anchors of the scale are placed in the description text for every question. Beside the scale a "Don't know" possibility will be added, as it is important to have answers for every possibility [Walonick, 2003]. With the question foundation and scale developed all the segments of the questionnaire will be described.

I.3 | Translation

A translation from English to Danish of the english question from ISO15666 is performed as the majority of participants are danish speaking.

Thinking about the last (12 months or so), when you are here at home, how much does noise from (noise source) bother, disturb or annoy you?

This can be translated into Danish as:

Tænk på de seneste (cirka 12 måneder) når du er hjemme, hvor meget generer, forstyrrer eller irriterer støj fra (støj kilde) dig?

To cross check the translation, according to [ISO 15666, 2003], back-translating the Danish sentence into English will result in:

Think about the latest (approximately 12 months when you are at home, how much does noise from (noise source) bother, disturb or annoy you?

This back-translation is deemed acceptable and the Danish translated sentence, discarding the last part with noise if it is not applicable, will be the foundation of the questions asked in the questionnaire.

I.4 | Questionnaire Segments

The questionnaire is divided into six different topics: cover letter, personal information, acoustic environment, acoustic comfort, noise annoyance, speech intelligibility, satisfaction and sensitivity calibration.

Cover Letter

The title of the questionnaire is: **The Dwellings Sound** which should be understood as a common term for room acoustics. The cover letter provides information about, background and purpose, a description of the questionnaire, how data is handled, confidentiality, volunteering and responsibility. All these are deemed important for the respondent [Walonick, 2003].

Background and Purpose

The background and purpose introduces what the survey is about and gives a description of the master project which the survey is part of (italic text is the questionnaire text).

This survey is part of a master project made by master students from Aalborg University. The purpose of this survey is to uncover how our dwellings affect sound and noise as well as how it affects us. The survey will be conducted in large parts of North Jutland in both houses and apartments.

The results are going to be used in an analysis where both the answers of the questionnaire and sound measurements are included. The comparison should answer which connection there is between the human perception and the dwellings influence on sound.

The purpose of the master project is to classify dwellings sound on a simple scale which everybody understands as dwellings sound is difficult to communicate. This could hopefully lead to people in the industry, home-owners and other parties interpreting sound in a more understandable way during design, construction and buying/renting.

Description

As the questionnaire is broken into different rooms for acoustic environment and acoustic comfort, refer to the acoustic environment description, is is described for the respondent. It is also described what the respondent should do if two or three of the rooms are openly connected.

In this questionnaire you will be presented questions regarding the sound in the following rooms:

- *Living room*
- *Kitchen*
- *Bedroom*

Should any of these rooms be openly connected, that means be gathered in one room, you are asked to still answer the questions for each room. For example should the living room and kitchen be connected. Then you must answer the questions regarding the kitchen as you were in that part of the room and answer the questions regarding the living room as you were in that part of the room.

Data Handling and Confidentiality

As the accompanying measurements can include personal information such as pictures from the dwelling and data such as address. It must be stated for the respondent that in the future these data could be published in a database.

The collected data will be your answers from this questionnaire, your address as well as the measurements which will be conducted or has been conducted. The data can be published on a database which is accessible to everybody. The data will however be anonymous.

Volunteering

As the survey is voluntarily it is described for the respondent that he or she is always entitled to stop the survey without reason.

If you want to participate in the survey it is voluntarily. You are able to at all times to interrupt the survey without reasons.

Responsibility

The last part of the cover letter supplies who the respondent can contact.

The main responsible for this survey are Kasper Kiis Jensen and Mikkel Krogh Simonsen, master students at Aalborg University. They can be contacted via mail: kkje13@student.aau.dk or mksi13@student.aau.dk.

Personal Information

The personal information segment asks for personal data which cannot be covered by the surveyor. Questions such as the address etc. is not asked about as this should be noted by the surveyor, as mentioned before the questionnaire is always accompanied by measurements. The questions asked are personal information such as gender and age which is needed to determine the population of the survey. Number of years living outside Denmark, which could influence the answers of the respondent due to other countries having other types of building standards. How long the respondent has lived in the dwelling, which could influence the answer due to the familiarization with the building. Number of residents and children in the dwelling, which is important due to the number of people having a great influence on room acoustics.

Gender	Woman ☐ Man ☐
Age	_____ Years
Number of years not settled in Denmark	_____ Years
How long have you been living in the dwelling	0-1 years ☐ 1-5 years ☐ 5- years ☐
Number of residents in the dwelling	_____ Persons
hereof kids under 13 years old	_____ Persons
Do you have any known hearing problems or do you use hearing aids	Yes ☐ No ☐

Acoustic Environment

Achieving a description of the acoustic environment which is simple to answer by the respondent and results in meaningful and comparable data is difficult. Project REBUS [Knudsen et al., 2017] tries by using a unipolar scale of a number of words where numerous of them are opposites of each other. The reason for using a unipolar scale is not known by the authors. It was however not seen as the best design due to consistency problems. As an example for this, marking a high score in two unipolar scales with opposite dimension e.g. quiet and noisy should result in inconsistent data. It was chosen to use Semantic Differential (SD) scales which measures respondents reactions to words. The reasons for using SD scales are that it is proven way of measuring respondents reactions and simple to understand. [Summers, 1970]

This however requires a change in scale design as SD scales are bipolar. The scale constructed, as seen on table I.3, is a seven point scale as this should be the preferred number of points in an SD scale if a neutral points is wanted [Al-Hindawe, 1996]. It is also chosen to label 3 as extremely , 2 as quite, 1 as slightly and 0 as neutral in the accompanying text as this should make the scale more understandable [Summers, 1970].

3	2	1	0	1	2	3
EXTREMELY	QUITE	SLIGHTLY	NEUTRAL	SLIGHTLY	QUITE	EXTREMELY

Table I.3: Constructed SD scale.

Ideally the words used in SD scales should be developed using proper a word elicitation [Al-Hindawe, 1996]. However because of time constraints this is not possible. The words found are therefore a product of an internal word elicitation and discussions with the projects supervisor, refer to Appendix J.

With the scale designed, the question asked should ask about the respondents feeling of their room acoustics. Room acoustics is however deemed a to technical term and the term *the rooms influence on sound so it feels* is used instead. Accompanying the question is a description of the how the scale works and an emphasis for the respondent to answer based on their immediate reaction.

It was originally decided to ask for the acoustic environment as a general question for the entire dwelling. It was however redesigned to ask about the acoustic environment of the living room, kitchen and bedroom which was deemed the three most common room. The reason for this redesign was that people would answer for different rooms on each scale instead of averaging them. The designed question for e.g. living room and accompanying scales can be seen below.

Thinking about the last 12 months or so, when you are here at home. Which word does best describe the living rooms influence on sound?
The scales describes opposites. For example if the living room influences sound such that it feels more dead than resounding then you should mark 3 for extremely dead, 2 for quite dead, 1 for

slightly dead. Mark 0 if it is neither. Please answer the questions with your immediate reaction. **The living room influences sound so it feels?**

	3	**2**	**1**	**0**	**1**	**2**	**3**	
Dead	☐	☐	☐	☐	☐	☐	☐	Resounding
Unclear	☐	☐	☐	☐	☐	☐	☐	Clear
Compact	☐	☐	☐	☐	☐	☐	☐	Spacious
Quiet	☐	☐	☐	☐	☐	☐	☐	Noisy
Uncomfortable	☐	☐	☐	☐	☐	☐	☐	Comfortable
Attenuated	☐	☐	☐	☐	☐	☐	☐	Amplified
Remote	☐	☐	☐	☐	☐	☐	☐	Enveloping
Soft	☐	☐	☐	☐	☐	☐	☐	Hard
Uneasy	☐	☐	☐	☐	☐	☐	☐	Calm
Absent	☐	☐	☐	☐	☐	☐	☐	Present

Acoustic Comfort

As an addition to the acoustic environment it is desired to have a description of the comfort of the respondent. The same scale design is used here as in the acoustic environment. The specific scales have been developed using an internal word elicitation, refer to Appendix J. The question asked is very simple as it ask to the respondents feelings towards different words again in different rooms. The designed question for e.g. living room and accompanying scales can be seen below.

Thinking about the last 12 months or so, when you are here at home. Which word does best describe the feeling you have when you are in the living room?
The scales describes opposites. For example if you feel more sleepy than awake then you should mark 3 for extremely sleepy, 2 for quite sleepy, 1 for slightly sleepy. Mark 0 if it is neither. Please answer the questions with your immediate reaction. **When I am in the living room I feel?**

	3	2	1	0	1	2	3	
Sleepy	☐	☐	☐	☐	☐	☐	☐	Awake
Enclosed	☐	☐	☐	☐	☐	☐	☐	Open
Uncomfortable	☐	☐	☐	☐	☐	☐	☐	Comfortable
Disinterested	☐	☐	☐	☐	☐	☐	☐	Committed
Small	☐	☐	☐	☐	☐	☐	☐	Large
Sad	☐	☐	☐	☐	☐	☐	☐	Happy
Dull	☐	☐	☐	☐	☐	☐	☐	Energetic
Pessimistic	☐	☐	☐	☐	☐	☐	☐	Optimistic
Inattentive	☐	☐	☐	☐	☐	☐	☐	Attentive
Uneasy	☐	☐	☐	☐	☐	☐	☐	Calm
Dispirited	☐	☐	☐	☐	☐	☐	☐	Lively
Stressed	☐	☐	☐	☐	☐	☐	☐	Relaxed

Noise

The scale now shifts to the original scale designed in section I.2 used for noise annoyance. The purpose of noise annoyance is to acquire the dwellings impact on noise. As it impossible for people sitting in the living room to disregard noise coming from the e.g. kitchen. It is chosen to ask about specific noise sources in the dwelling instead of asking about noise in the living room, kitchen and bedroom. The different noise sources stated should be able to cover most of the different kind of normal noises sources which could be present inside a dwelling. If the respondent has a noise source which is not specified the respondent can add it to the list and rate it on the same scale as the specified ones.

Thinking about the last 12 months or so, when you are here at home how much does **noise from inside you dwelling bother, disturb or annoy you?**
The scales go from 0 to 10 where 0 is not at all and 10 is extremely.

	0	1	2	3	4	5	6	7	8	9	10	Don't know
Unwanted speech	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Furniture being dragged across the floor	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Clinging porcelain or ceramics	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Slamming doors	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Electric appliances (TV, loudspeakers, consoles)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Appliances (freezer, refrigerator)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Kitchen tools (blender, food processor)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Technical installations (exhaust hood, air condition)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Other noise: ____________________	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Speech Intelligibility

Speech intelligibility was determined an important attribute for the purpose of the room and it was therefore determined to include it in the questionnaire. The designed segment for speech intelligibility was designed mostly based on the number of people in the room. As the number of people in a room has a great affect on speech intelligibility.

Thinking about the last 12 months or so, when you are here at home how difficult is it to understand speech?
The scales describe speech intelligibility from 0 to 10 where 0 is not at all difficult and 10 is extremely difficult.

	0	1	2	3	4	5	6	7	8	9	10	Don't know
In your daily life e.g. when there is conversation or the TV is on	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
When there are guest (between 2 and 6 persons)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
When there are larger gatherings (more than 6 persons)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
When there are playing kids in the room	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

It was however chosen to leave this segment out of the final questionnaire for several reasons. It was deemed difficult for people to answer the question as speech intelligibility is usually not something people consider. As respondents are not screened hearing impairments could have a large affect on speech intelligibility. Some of the SD scales (unclear - clear) should overlap with speech intelligibility.

Satisfaction

The respondent is also asked to rate their acoustic satisfaction with their living room, kitchen and bedroom. The purpose of this segment is to have a direct satisfaction rating. As with the other questions the acoustic satisfaction term is swapped with *with the rooms influence on sound*. The scale design is the same as with noise annoyance.

Thinking about the last 12 months or so, when you are here at home **how satisfied are you with the rooms influence on sound** in the following rooms?
The scales describe satisfaction from 0 to 10 where 0 is extremely unsatisfied, 5 is neither and 10 is extremely satisfied.

	0	1	2	3	4	5	6	7	8	9	10	Don't know
Living room	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Kitchen	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Bedroom	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Sensitivity

The last part of questionnaire is a measure of how sensitive the respondent is. This is important to monitor as the questionnaire answers should be comparable with other persons answer. This is measured by asking the respondent to rate their annoyance in different scenarios instead of asking the respondent directly for their sensitivity as this question could be difficult to answer.

How much would **you feel bothered, disturbed or annoyed in the following scenario?**
The scales describes annoyance from 0 to 10 where 0 is not at all annoyed, 2 is slightly annoyed, 5 is moderately annoyed, 8 is very annoyed and 10 is extremely annoyed.

	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Don't know**
When you are in a resounding room	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
When the TV or radio is turned up	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
When the neighbour is having a party	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
When a lot of people talk at the same time	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

J | Word Elicitation

This appendix documents the procedure mentioned in chapter 4 concerning the questionnaire development which includes word elicitations, brainstorms, selection and sorting processes etc. and Danish translations. It should be noted that all parts of the questionnaire and supplying material is written in Danish and only the describing text is in English. The questionnaire in its full length can be found in Danish, refer to Appendix L, and in English, refer to Appendix K.

Development flow

The questions covering personal information has been derived using a brainstorm. The scales for the questionnaire have been developed using the following approach:

1. Be exposed to different kinds of rooms and word elicitate based on the experience to cover all potential descriptors that can be used as scales.
2. Sort for redundant descriptors.
3. list all words into bipolar pairs, again discarding potentially redundant descriptors.

J.1 | Personal information

Brainstorm

A brainstorm was conducted with drawn inspiration from [Knudsen et al., 2017], [Rasmussen and Machimbarrena, 2014a] and [ISO 15666, 2003]. The following questions were produced:

- Hvad er dit køn?
- Hvad er din alder?
- Hvad er din følsomhed overfor støj?
- Hvordan er dit helbred?
- Hvor længe har du boet i din bolig?
- Hvor mange bor i din bolig?
- Hvor mange børn bor der i din bolig?
- Hvad er børnenes alder?
- Er du født i Danmark?
- Hvad er dit uddannelses niveau?
- Er du i beskæftigelse?
- Hvad er din månedlige indkomst?
- Vil du anbefale din lejlighed til andre?
- Yderligere kommentarer?
- Må vi kontakte dig om foretagelse af lydmålinger?

Discarded

The following questions were discarded, due to either being irrelevant or being to personal:

- Hvad er din følsomhed overfor støj?
- Hvordan er dit helbred?
- Hvad er børnenes alder?
- Er du født i Danmark?
- Hvad er dit uddannelses niveau?
- Er du i beskæftigelse?
- Hvad er din månedlige indkomst?
- Vil du anbefale din lejlighed til andre?
- Yderligere kommentarer?
- Må vi kontakte dig om foretagelse af lydmålinger?

Final List

The final list of questions are:

- Hvad er dit køn?
- Hvad er din alder?
- Hvor længe har du boet i din bolig?
- Hvor mange bor i din bolig?
- Hvor mange børn bor der i din bolig?

J.2 | Acoustic Environment

Word Elicitation

A word elicitation was conducted with inspiration from [Knudsen et al., 2017]. The following words were produced:

- Stille
- Blød
- Dæmpet
- Høj
- Hård
- Behagelig
- Skarp
- Bekvemmelig
- Støjende
- Skramlende
- Ubehagelig
- Ekkoende
- Mudret
- Let
- Afdæmpet
- Rolig
- Kværnende
- Lydt
- Varm
- Kold
- God
- Dårlig
- Stærk
- Svag
- Tydelig
- Utydelig
- Præcis
- Upræcis
- Klar
- Urolig
- Forstyrrende
- Tung
- Omsluttende
- Indelukket
- Omkransende
- Distancerende
- Mild
- Nærværende
- Fjern
- Beroligende
- Irriterende
- Klangfyldt
- Afslørende
- Stor
- Lun
- Idyllisk
- Klaustrofobisk
- Kompakt
- Kedelig
- Disorienterende
- Fraværende
- Tør
- Klinisk
- Grumset
- Rummelig
- Kraftig
- Dødt
- Rungende

Redundancies

Some words are redundant and were discarded:

Word	Redundant words	Replaced with
Omsluttende	Omkransende	Omsluttende
Utydelig	Grumset, Mudret, Upræcis	Utydelig
Behagelig	Bekvemmelig	Behagelig
Varm	Lun	Varm
Tydelig	Præcis, Klar, Skarp, Afslørende	Tydelig
Rolig	Beroligende	Rolig
Kraftig	Stærk, Høj, Stor	Kraftig
Støjende	Skramlende, Forstyrrende, Irriterende	Støjende
Dæmpet	Afdæmpet	Dæmpet
Mild	Svag	Mild
Kompakt	Indelukket	Kompakt
Rungende	Ekkoende, Klangfyldt	Rungende
Fjern	Distancerende, Kedelig	Fjern
Død	Tør, Klinisk	Død

Discarded

Some words were discarded because they were to difficult to understand or not applicable enough for an acoustic description:

- Idyllisk
- Surrende
- Klaustrofobisk
- Kværnende
- Disorienterende

Scaling

The remaining words were set up in bipolar scales:

Dårlig - God	Blød - Hård
Kold - Varm	Stille - Støjende
Let - Tung	Mild - Kraftig
Utydelig - Tydelig	Kompakt - Rummelig
Urolig - Rolig	Dæmpet - Lydt
Ubehagelig - Behagelig	Død - Rungende
Fraværende - Nærværende	Fjern - Omsluttende

Sorting

Some of the scales were sorted out because they were not describing enough or were not applicable to the acoustic description:

Dårlig - God	Kold - Varm
Let - Tung	Mild - Kraftig

Final List

The final list of scales are:

Død - Rungende

Utydelig - Tydelig

Kompakt - Rummelig

Stille - Støjende

Ubehagelig - Behagelig

Dæmpet - Lydt

Fjern - Omsluttende

Blød - Hård

Urolig - Rolig

Fraværende - Nærværende

J.3 | Acoustic Comfort

The acoustic comfort scales were derived using the same methodology as the acoustic description.

Word Elicitation

- Søvnig
- Vågen
- Utilfreds
- Tilfreds
- Du keder dig
- Interesseret
- Anspændt
- Afslappet
- Afdæmpet
- Munter
- Pessimistisk
- Optimistisk
- Energisk
- Ked af det
- Glad
- Uengageret
- Engageret
- Urolig
- Rolig
- Sløv
- Livlig
- Nedslået
- Nervøs
- Livløs
- Tilpas
- Utilpas
- Åben
- Lukket
- Stresset
- Stor
- Lille
- Indelukket
- Uinteresseret
- Bevægelig
- Fastlåst
- Forvirret
- Træt
- Nysgerrig
- Mindfull
- Eftertænksom
- Selvbevidst
- Opmærksom
- Umotiveret
- Irriteret
- Vred
- Stemningsfuld
- Afventende
- Uopmærksom

Redundancies

Word	Redundant words	Replaced with
Afslappet	Afdæmpet	Afslappet
Indelukket	Lukket	Indelukket
Eftertænksom	Mindfull, Selvbevidst	Eftertænksom
Glad	Munter	Glad
Engageret	Interesseret	Engageret
Uengageret	Uinteresseret	Uengageret
Sløv	Træt, Kedelig	Sløv
Nedslået	Livløs	Nedslået
Livlig	Bevægelig	Livlig
Stresset	Anspændt	Stresset

Discarded

- Nervøs
- Fastlåst
- Forvirret
- Afventende
- Stemningsfuld
- Vred
- Irriteret
- Eftertænksom
- Nysgerrig

Scaling

Søvnig - Vågen

Utilfreds - Tilfreds

Uengageret - Engageret

Urolig - Rolig

Pessimistisk - Optimistisk

Uopmærksom - Opmærksom

Nedslået - Livlig

Utilpas - Tilpas

Lille - Stor

Stresset - Afslappet

Sløv - Energisk

Ked af det - Glad

Indelukket - Åben

Sorting

Utilfreds - Tilfreds

Final List

Søvnig - Vågen

Indelukket - Åben

Utilpas - Tilpas

Uengageret - Engageret

Lille - Stor

Ked af det - Glad

Sløv - Energisk

Pessimistisk - Optimistisk

Uopmærksom - Opmærksom

Urolig - Rolig

Nedslået - Livlig

Stresset - Afslappet

K | Questionnaire: The Dwellings Sound

A .pdf version of the report can be found at `CD:/StandAloneQuestionaireEnglish.pdf`

Questionnaire: The Dwellings Sound

Background and Purpose

This survey is part of a master project made by master students from Aalborg University. The purpose of this survey is to uncover how our dwellings affect sound and noise as well as how it affects us. The survey will be conducted in large parts of North Jutland in both houses and apartments.

The results are going to be used in an analysis where both the answers of the questionnaire and sound measurements are included. The comparison should answer which connection there is between the human perception and the dwellings influence on sound.

The purpose of the master project is to classify dwellings sound on a simple scale which everybody understands as dwellings sound is difficult to communicate. This could hopefully lead to people in the industry, home-owners and other parties interpreting sound in a more understandable way during design, construction and buying/renting.

Description

In this questionnaire you will be presented questions regarding the sound in the following rooms:

- Living room
- Kitchen
- Bedroom

Should any of these rooms be openly connected, that means be gathered in one room, you are asked to still answer the questions for each room. For example should the living room and kitchen be connected. Then you must answer the questions regarding the kitchen as you were in that part of the room and answer the questions regarding the living room as you were in that part of the room.

Data Handling and Confidentiality

The collected data will be your answers from this questionnaire, your address as well as the measurements which will be conducted or has been conducted. The data can be published on a database which is accessible to everybody. The data will however be anonymous.

Volunteering

If you want to participate in the survey it is voluntarily. You are able to at all times to interrupt the survey without reasons.

Responsibility

The main responsible for this survey are Kasper Kiis Jensen and Mikkel Krogh Simonsen, master students at Aalborg University. They can be contacted via mail: kkje13@student.aau.dk or mksi13@student.aau.dk.

Personal Information

Initially we would like to ask you some questions regarding you and your dwelling.

Gender	Woman ☐ Man ☐
Age	______ Years
Number of years not settled in Denmark	______ Years
How long have you been living in the dwelling	0-1 years ☐ 1-5 years ☐ 5- years ☐
Number of residents in the dwelling	______ Persons
hereof kids under 13 years old	______ Persons
Do you have any known hearing problems or do you use hearing aids	Yes ☐ No ☐

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Sound (Living Room)

Thinking about the last 12 months or so, when you are here at home. Which word does best describe the living rooms influence on sound?
The scales describes opposites. For example if the living room influences sound such that it feels more dead than resounding then you should mark 3 for extremely dead, 2 for quite dead, 1 for slightly dead. Mark 0 if it is neither. Please answer the questions with your immediate reaction. **The living room influences sound so it feels?**

	3	2	1	0	1	2	3	
Dead	☐	☐	☐	☐	☐	☐	☐	Resounding
Unclear	☐	☐	☐	☐	☐	☐	☐	Clear
Compact	☐	☐	☐	☐	☐	☐	☐	Spacious
Quiet	☐	☐	☐	☐	☐	☐	☐	Noisy
Uncomfortable	☐	☐	☐	☐	☐	☐	☐	Comfortable
Attenuated	☐	☐	☐	☐	☐	☐	☐	Amplified
Remote	☐	☐	☐	☐	☐	☐	☐	Enveloping
Soft	☐	☐	☐	☐	☐	☐	☐	Hard
Uneasy	☐	☐	☐	☐	☐	☐	☐	Calm
Absent	☐	☐	☐	☐	☐	☐	☐	Present

Comfort (Living Room)

Thinking about the last 12 months or so, when you are here at home. Which word does best describe the feeling you have when you are in the living room?
The scales describes opposites. For example if you feel more sleepy than awake then you should mark 3 for extremely sleepy, 2 for quite sleepy, 1 for slightly sleepy. Mark 0 if it is neither. Please answer the questions with your immediate reaction. **When I am in the living room I feel?**

	3	2	1	0	1	2	3	
Sleepy	☐	☐	☐	☐	☐	☐	☐	Awake
Enclosed	☐	☐	☐	☐	☐	☐	☐	Open
Uncomfortable	☐	☐	☐	☐	☐	☐	☐	Comfortable
Disinterested	☐	☐	☐	☐	☐	☐	☐	Committed
Small	☐	☐	☐	☐	☐	☐	☐	Large
Sad	☐	☐	☐	☐	☐	☐	☐	Happy
Dull	☐	☐	☐	☐	☐	☐	☐	Energetic
Pessimistic	☐	☐	☐	☐	☐	☐	☐	Optimistic
Inattentive	☐	☐	☐	☐	☐	☐	☐	Attentive
Uneasy	☐	☐	☐	☐	☐	☐	☐	Calm
Dispirited	☐	☐	☐	☐	☐	☐	☐	Lively
Stressed	☐	☐	☐	☐	☐	☐	☐	Relaxed

Sound (Kitchen)

Thinking about the last 12 months or so, when you are here at home. Which word does best describe the kitchens influence on sound?
The scales describes opposites. For example if the kitchen influences sound such that it feels more dead than resounding then you should mark 3 for extremely dead, 2 for quite dead, 1 for slightly dead. Mark 0 if it is neither. Please answer the questions with your immediate reaction. **The kitchen influences sound so it feels?**

	3	**2**	**1**	**0**	**1**	**2**	**3**	
Dead	☐	☐	☐	☐	☐	☐	☐	Resounding
Unclear	☐	☐	☐	☐	☐	☐	☐	Clear
Compact	☐	☐	☐	☐	☐	☐	☐	Spacious
Quiet	☐	☐	☐	☐	☐	☐	☐	Noisy
Uncomfortable	☐	☐	☐	☐	☐	☐	☐	Comfortable
Attenuated	☐	☐	☐	☐	☐	☐	☐	Amplified
Remote	☐	☐	☐	☐	☐	☐	☐	Enveloping
Soft	☐	☐	☐	☐	☐	☐	☐	Hard
Uneasy	☐	☐	☐	☐	☐	☐	☐	Calm
Absent	☐	☐	☐	☐	☐	☐	☐	Present

Comfort (Kitchen)

Thinking about the last 12 months or so, when you are here at home. Which word does best describe the feeling you have when you are in the kitchen?
The scales describes opposites. For example if you feel more sleepy than awake then you should mark 3 for extremely sleepy, 2 for quite sleepy, 1 for slightly sleepy. Mark 0 if it is neither. Please answer the questions with your immediate reaction. **When I am in the kitchen I feel?**

	3	**2**	**1**	**0**	**1**	**2**	**3**	
Sleepy	☐	☐	☐	☐	☐	☐	☐	Awake
Enclosed	☐	☐	☐	☐	☐	☐	☐	Open
Uncomfortable	☐	☐	☐	☐	☐	☐	☐	Comfortable
Disinterested	☐	☐	☐	☐	☐	☐	☐	Committed
Small	☐	☐	☐	☐	☐	☐	☐	Large
Sad	☐	☐	☐	☐	☐	☐	☐	Happy
Dull	☐	☐	☐	☐	☐	☐	☐	Energetic
Pessimistic	☐	☐	☐	☐	☐	☐	☐	Optimistic
Inattentive	☐	☐	☐	☐	☐	☐	☐	Attentive
Uneasy	☐	☐	☐	☐	☐	☐	☐	Calm
Dispirited	☐	☐	☐	☐	☐	☐	☐	Lively
Stressed	☐	☐	☐	☐	☐	☐	☐	Relaxed

Sound (Bedroom)

Thinking about the last 12 months or so, when you are here at home. Which word does best describe the bedrooms influence on sound?
The scales describes opposites. For example if the bedroom influences sound such that it feels more dead than resounding then you should mark 3 for extremely dead, 2 for quite dead, 1 for slightly dead. Mark 0 if it is neither. Please answer the questions with your immediate reaction. **The bedroom influences sound so it feels?**

	3	**2**	**1**	**0**	**1**	**2**	**3**	
Dead	☐	☐	☐	☐	☐	☐	☐	Resounding
Unclear	☐	☐	☐	☐	☐	☐	☐	Clear
Compact	☐	☐	☐	☐	☐	☐	☐	Spacious
Quiet	☐	☐	☐	☐	☐	☐	☐	Noisy
Uncomfortable	☐	☐	☐	☐	☐	☐	☐	Comfortable
Attenuated	☐	☐	☐	☐	☐	☐	☐	Amplified
Remote	☐	☐	☐	☐	☐	☐	☐	Enveloping
Soft	☐	☐	☐	☐	☐	☐	☐	Hard
Uneasy	☐	☐	☐	☐	☐	☐	☐	Calm
Absent	☐	☐	☐	☐	☐	☐	☐	Present

Comfort (Bedroom)

Thinking about the last 12 months or so, when you are here at home. Which word does best describe the feeling you have when you are in the bedroom?
The scales describes opposites. For example if you feel more sleepy than awake then you should mark 3 for extremely sleepy, 2 for quite sleepy, 1 for slightly sleepy. Mark 0 if it is neither. Please answer the questions with your immediate reaction. **When I am in the bedroom I feel?**

	3	**2**	**1**	**0**	**1**	**2**	**3**	
Sleepy	☐	☐	☐	☐	☐	☐	☐	Awake
Enclosed	☐	☐	☐	☐	☐	☐	☐	Open
Uncomfortable	☐	☐	☐	☐	☐	☐	☐	Comfortable
Disinterested	☐	☐	☐	☐	☐	☐	☐	Committed
Small	☐	☐	☐	☐	☐	☐	☐	Large
Sad	☐	☐	☐	☐	☐	☐	☐	Happy
Dull	☐	☐	☐	☐	☐	☐	☐	Energetic
Pessimistic	☐	☐	☐	☐	☐	☐	☐	Optimistic
Inattentive	☐	☐	☐	☐	☐	☐	☐	Attentive
Uneasy	☐	☐	☐	☐	☐	☐	☐	Calm
Dispirited	☐	☐	☐	☐	☐	☐	☐	Lively
Stressed	☐	☐	☐	☐	☐	☐	☐	Relaxed

Noise

Thinking about the last 12 months or so, when you are here at home how much does **noise from inside your dwelling bother, disturb or annoy you?**
The scales go from 0 to 10 where 0 is not at all and 10 is extremely.

	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Don't know**
Unwanted speech	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Furniture being dragged across the floor	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Clinging porcelain or ceramics	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Slamming doors	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Electric appliances (TV, loud-speakers, consoles)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Appliances (freezer, refrigerator)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Kitchen tools (hand mixer, blender, food processor)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Technical installations (exhaust hood, air condition)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Other noise: ____________________	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Satisfaction

Thinking about the last 12 months or so, when you are here at home **how satisfied are you with the rooms influence on sound** in the following rooms?
The scales describe satisfaction from 0 to 10 where 0 is extremely unsatisfied, 5 is neither and 10 is extremely satisfied.

	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Don't know**
Living room	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Kitchen	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Bedroom	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Sensitivity

How much would **you feel bothered, disturbed or annoyed in the following scenario?**
The scales go from 0 to 10 where 0 is not at all and 10 is extremely.

	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Don't know**
When you are in a resounding room	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
When the TV or radio is turned up	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
When the neighbour is having a party	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
When a lot of people talk at the same time	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

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L | Spørgeskema: Boligens Lyd

A .pdf version of the report can be found at `CD:/StandAloneQuestionaire.pdf`

Spørgeskema: Boligens Lyd

Baggrund og Formål

Denne undersøgelse er en del af et speciale udført af kandidatstuderende fra Aalborg Universitet. Undersøgelsen har til formål at afdække hvordan vores boliger påvirker lyd og støj, samt hvordan dette påvirker os. Undersøgelsen vil blive foretaget i store dele af Nordjylland i både huse og lejligheder.

Resultaterne skal bruges i en analyse hvor både spørgeskemasvar og lydmålinger indgår. Sammenligningen skal give svar på hvilken sammenhæng der er mellem den menneskelige opfattelse og boligens påvirkning på lyden.

Specialets formål er at kunne klassificere boligers lyd, på en simpel skala som alle forstår, da dette indtil nu har været svært at formidle. Dette kan forhåbentligt medføre at folk i industrien, boligejere og andre involverede har nemmere ved at fortolke lyd under design, konstruktion og køb/leje.

Beskrivelse

Du vil i denne undersøgelse blive præsenteret for spørgsmål angående lyden i følgende rum:

- Stue
- Køkken
- Soveværelse

Skulle nogle af disse rum være åbent forbundne-det vil sige være i et samlet rum bedes du stadig besvare spørgsmålene for hvert rum. For eksempel skulle stue og køkken være forbundet, skal du svare på køkken-spørgsmålene som befandt du dig i den del af rummet og svare på stue-spørgsmålene som befandt du dig i den del af rummet.

Håndtering af data og fortrolighed

De data der indsamles, er dine svar på spørgeskemaet, din adresse samt de målinger der foretages eller har været foretaget. Dataene kan blive lagt offentligt tilgængelig på en database som kan tilgås af alle, men vil i så fald blive anonymiseret.

Frivillighed

Det er frivilligt om du vil deltage i denne undersøgelse. Du kan til enhver tid afbryde undersøgelsen uden begrundelse.

Ansvarlig

Hovedansvarlig for denne undersøgelse er Kasper Kiis Jensen og Mikkel Krogh Simonsen, kandidat studerende på Aalborg Universitet. Disse kan kontaktes via mail: kkje13@student.aau.dk eller mksi13@student.aau.dk.

Personlig Information

Indledningsvis vil vi gerne stille dig nogle spørgsmål som omhandler dig og din bolig.

Køn	Kvinde ☐ Mand ☐
Alder	_____ År
Antal år ikke bosat i Danmark	_____ År
Hvor lang tid har du boet i boligen	0-1 år ☐ 1-5 år ☐ 5- år ☐
Antal beboere i boligen	_____ Personer
Heraf børn under 13 år i boligen	_____ Personer
Har du kendte høreproblemer eller bruger du høreapparat	Ja ☐ Nej ☐

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Lyd (Stuen)

Tænk på de seneste cirka 12 måneder når du er hjemme. Hvilket ord beskriver bedst stuens påvirkning af lyd? *Skalaerne beskriver modsætninger, så for eksempel hvis stuen påvirker lyd så den føles mere død end rungende, angiver du 3 for ekstrem død, 2 for noget død, 1 for lidt død. Angiv 0 hvis du er hverken/eller. Svar gerne på spørgsmålene med din umiddelbare reaktion.* **Stuen påvirker lyd så den føles?**

	3	2	1	0	1	2	3	
Død	☐	☐	☐	☐	☐	☐	☐	Rungende
Utydelig	☐	☐	☐	☐	☐	☐	☐	Tydelig
Kompakt	☐	☐	☐	☐	☐	☐	☐	Rummelig
Stille	☐	☐	☐	☐	☐	☐	☐	Støjende
Ubehagelig	☐	☐	☐	☐	☐	☐	☐	Behagelig
Dæmpet	☐	☐	☐	☐	☐	☐	☐	Kraftig
Fjern	☐	☐	☐	☐	☐	☐	☐	Omsluttende
Blød	☐	☐	☐	☐	☐	☐	☐	Hård
Urolig	☐	☐	☐	☐	☐	☐	☐	Rolig
Fraværende	☐	☐	☐	☐	☐	☐	☐	Nærværende

Komfort (Stuen)

Tænk på de seneste cirka 12 måneder når du er hjemme. Hvilket ord beskriver bedst følelsen du har når du er i stuen?
Skalaerne beskriver modsætninger, så for eksempel hvis du føler dig mere søvnig end vågen, angiver du 3 for ekstrem søvnig, 2 for noget søvnig, 1 for lidt søvnig. Angiv 0 hvis du er hverken/eller. Svar gerne på spørgsmålene med din umiddelbare reaktion. **Når jeg er i stuen føler jeg mig?**

	3	2	1	0	1	2	3	
Søvnig	☐	☐	☐	☐	☐	☐	☐	Vågen
Indelukket	☐	☐	☐	☐	☐	☐	☐	Åben
Utilpas	☐	☐	☐	☐	☐	☐	☐	Tilpas
Uengageret	☐	☐	☐	☐	☐	☐	☐	Engageret
Lille	☐	☐	☐	☐	☐	☐	☐	Stor
Ked af det	☐	☐	☐	☐	☐	☐	☐	Glad
Sløv	☐	☐	☐	☐	☐	☐	☐	Energisk
Pessimistisk	☐	☐	☐	☐	☐	☐	☐	Optimistisk
Uopmærksom	☐	☐	☐	☐	☐	☐	☐	Opmærksom
Urolig	☐	☐	☐	☐	☐	☐	☐	Rolig
Nedslået	☐	☐	☐	☐	☐	☐	☐	Livlig
Stresset	☐	☐	☐	☐	☐	☐	☐	Afslappet

Lyd (Køkkenet)

Tænk på de seneste cirka 12 måneder når du er hjemme. Hvilket ord beskriver bedst køkkenets påvirkning af lyd?
Skalaerne beskriver modsætninger, så for eksempel hvis køkkenet påvirker lyd så den føles mere død end rungende, angiver du 3 for ekstrem død, 2 for noget død, 1 for lidt død. Angiv 0 hvis du er hverken/eller. Svar gerne på spørgsmålene med din umiddelbare reaktion. **Køkkenet påvirker lyd så den føles?**

	3	**2**	**1**	**0**	**1**	**2**	**3**	
Død	☐	☐	☐	☐	☐	☐	☐	Rungende
Utydelig	☐	☐	☐	☐	☐	☐	☐	Tydelig
Kompakt	☐	☐	☐	☐	☐	☐	☐	Rummelig
Stille	☐	☐	☐	☐	☐	☐	☐	Støjende
Ubehagelig	☐	☐	☐	☐	☐	☐	☐	Behagelig
Dæmpet	☐	☐	☐	☐	☐	☐	☐	Kraftig
Fjern	☐	☐	☐	☐	☐	☐	☐	Omsluttende
Blød	☐	☐	☐	☐	☐	☐	☐	Hård
Urolig	☐	☐	☐	☐	☐	☐	☐	Rolig
Fraværende	☐	☐	☐	☐	☐	☐	☐	Nærværende

Komfort (Køkkenet)

Tænk på de seneste cirka 12 måneder når du er hjemme. Hvilket ord beskriver bedst følelsen du har når du er i køkkenet?
Skalaerne beskriver modsætninger, så for eksempel hvis du føler dig mere søvnig end vågen, angiver du 3 for ekstrem søvnig, 2 for noget søvnig, 1 for lidt søvnig. Angiv 0 hvis du er hverken/eller. Svar gerne på spørgsmålene med din umiddelbare reaktion. **Når jeg er i køkkenet føler jeg mig?**

	3	**2**	**1**	**0**	**1**	**2**	**3**	
Søvnig	☐	☐	☐	☐	☐	☐	☐	Vågen
Indelukket	☐	☐	☐	☐	☐	☐	☐	Åben
Utilpas	☐	☐	☐	☐	☐	☐	☐	Tilpas
Uengageret	☐	☐	☐	☐	☐	☐	☐	Engageret
Lille	☐	☐	☐	☐	☐	☐	☐	Stor
Ked af det	☐	☐	☐	☐	☐	☐	☐	Glad
Sløv	☐	☐	☐	☐	☐	☐	☐	Energisk
Pessimistisk	☐	☐	☐	☐	☐	☐	☐	Optimistisk
Uopmærksom	☐	☐	☐	☐	☐	☐	☐	Opmærksom
Urolig	☐	☐	☐	☐	☐	☐	☐	Rolig
Nedslået	☐	☐	☐	☐	☐	☐	☐	Livlig
Stresset	☐	☐	☐	☐	☐	☐	☐	Afslappet

Lyd (Soveværelset)

Tænk på de seneste cirka 12 måneder når du er hjemme. Hvilket ord beskriver bedst soveværelsets påvirkning af lyd?
Skalaerne beskriver modsætninger, så for eksempel hvis soveværelset påvirker lyd så den føles mere død end rungende, angiver du 3 for ekstrem død, 2 for noget død, 1 for lidt død. Angiv 0 hvis du er hverken/eller. Svar gerne på spørgsmålene med din umiddelbare reaktion. **Soveværelset påvirker lyd så den føles?**

	3	**2**	**1**	**0**	**1**	**2**	**3**	
Død	☐	☐	☐	☐	☐	☐	☐	Rungende
Utydelig	☐	☐	☐	☐	☐	☐	☐	Tydelig
Kompakt	☐	☐	☐	☐	☐	☐	☐	Rummelig
Stille	☐	☐	☐	☐	☐	☐	☐	Støjende
Ubehagelig	☐	☐	☐	☐	☐	☐	☐	Behagelig
Dæmpet	☐	☐	☐	☐	☐	☐	☐	Kraftig
Fjern	☐	☐	☐	☐	☐	☐	☐	Omsluttende
Blød	☐	☐	☐	☐	☐	☐	☐	Hård
Urolig	☐	☐	☐	☐	☐	☐	☐	Rolig
Fraværende	☐	☐	☐	☐	☐	☐	☐	Nærværende

Komfort (Soveværelset)

Tænk på de seneste cirka 12 måneder når du er hjemme. Hvilket ord beskriver bedst følelsen du har når du er i soveværelset?
Skalaerne beskriver modsætninger, så for eksempel hvis du føler dig mere søvnig end vågen, angiver du 3 for ekstrem søvnig, 2 for noget søvnig, 1 for lidt søvnig. Angiv 0 hvis du er hverken/eller. Svar gerne på spørgsmålene med din umiddelbare reaktion. **Når jeg er i soveværelset føler jeg mig?**

	3	**2**	**1**	**0**	**1**	**2**	**3**	
Søvnig	☐	☐	☐	☐	☐	☐	☐	Vågen
Indelukket	☐	☐	☐	☐	☐	☐	☐	Åben
Utilpas	☐	☐	☐	☐	☐	☐	☐	Tilpas
Uengageret	☐	☐	☐	☐	☐	☐	☐	Engageret
Lille	☐	☐	☐	☐	☐	☐	☐	Stor
Ked af det	☐	☐	☐	☐	☐	☐	☐	Glad
Sløv	☐	☐	☐	☐	☐	☐	☐	Energisk
Pessimistisk	☐	☐	☐	☐	☐	☐	☐	Optimistisk
Uopmærksom	☐	☐	☐	☐	☐	☐	☐	Opmærksom
Urolig	☐	☐	☐	☐	☐	☐	☐	Rolig
Nedslået	☐	☐	☐	☐	☐	☐	☐	Livlig
Stresset	☐	☐	☐	☐	☐	☐	☐	Afslappet

Støj

Tænk på de seneste cirka 12 måneder når du er hjemme. I hvilken grad er du **forstyrret/irriteret/generet af følgende støj indefra din bolig?**
Skalaerne går fra 0 til 10, hvor 0 er slet ikke og 10 er ekstremt.

	0	1	2	3	4	5	6	7	8	9	10	Ved ikke
Uønsket tale.	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Møbler der trækkes hen over gulvet.	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Klirrende porcelæn eller keramik.	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Smækkende døre	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Elektriske apparater (TV, højtaler, spillemaskiner)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Hårde hvidevare (fryser, køleskabe)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Køkkenredskaber (håndmixer, blender, foodprocessor).	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Tekniske installationer (emhætte, aircondition).	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Andet støj: ____________	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Tilfredshed

Tænk på de seneste cirka 12 måneder når du er hjemme. I hvilken grad er du **tilfreds med rummets påvirkning på lyd** i følgende rum?
Skalaerne beskriver tilfredshed fra 0 til 10 hvor 0 er ekstremt utilfreds, 5 er hverken eller og 10 er ekstremt tilfreds.

	0	1	2	3	4	5	6	7	8	9	10	Ved ikke
Stue	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Køkken	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Soveværelse	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Følsomhed

I hvilken grad ville du **føle dig forstyrret/irriteret/generet** i følgende scenarie?
Skalaerne går fra 0 til 10, hvor 0 er slet ikke og 10 er ekstremt.

	0	1	2	3	4	5	6	7	8	9	10	Ved ikke
Når du befinder dig i ekkoende rum.	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Når der er skruet højt op for TV eller radio o.lign.	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Når naboen holder fest	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Når mange snakker på samme tid	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

M | Data Analysis

The purpose of this appendix is to document, analyze and interpret the data in-depth, acquired from dwellings during the measurement campaign. The goal of the analysis is to be able to make a classification from one or several measured parameters. The appendix is split into three main topics; measurement analysis, questionnaire analysis and a combined data analysis.

A total of 45 ISO3382-2 precision methods were carried out in 15 different furnished dwellings. In each dwelling the rooms measured were; living room, kitchen and bedroom. The database can be found in the enclosed appendix folder under `DataProcessing/LoadedDatabase.csv`. It contains for each room a measurement journal (.pdf), a single page result (.pdf), raw measurements (.mat), impulse responses (.mat) and reverberation results (.mat). The answers for the questionnaire is linked to each dwelling as (.csv).

M.1 | Measurements: Data

The measurement data will first be presented to give an overview of the dataset. As presenting the impulse responses provides little understanding these will not be showed. To portrait the quality of the impulse responses a distribution of the impulse-to-noise (INR) for each frequency band can be seen on figure M.1.

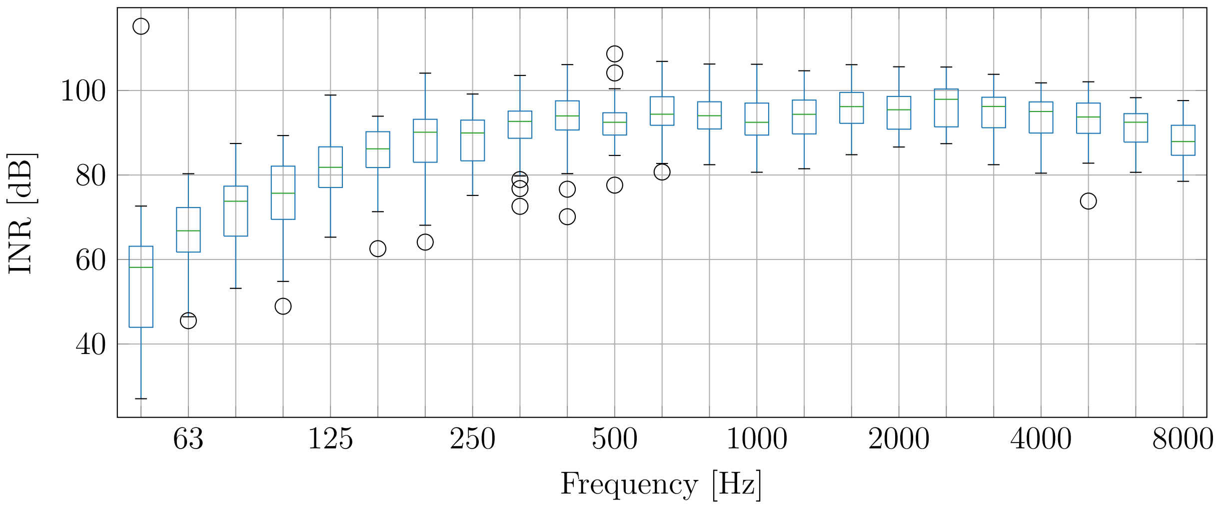


Figure M.1: Box plot of INR for each frequency band.

As it can be seen the INR decreases at the lower frequency bands which is to be expected in domestic rooms because of ventilation, traffic noise etc. If the INR is below 35 dB it means that a T_{20} time could not be achieved. A distribution of the number of measurements used to average the respective reverberation time can be seen on figure M.2. The 50 Hz band uses an average of 10 measurements, however 25 % percent of the data uses below four measurements. The 50 Hz band is therefore discarded in the analysis. The 63 Hz band also have several outliers but is not discarded. The reason for the outliers is that two different Bruel & Kjaer Omni Powers were used when measuring. One of the models could not supply the needed SPL at the two lower bands. The frequency response of the two models can be seen in Appendix N.

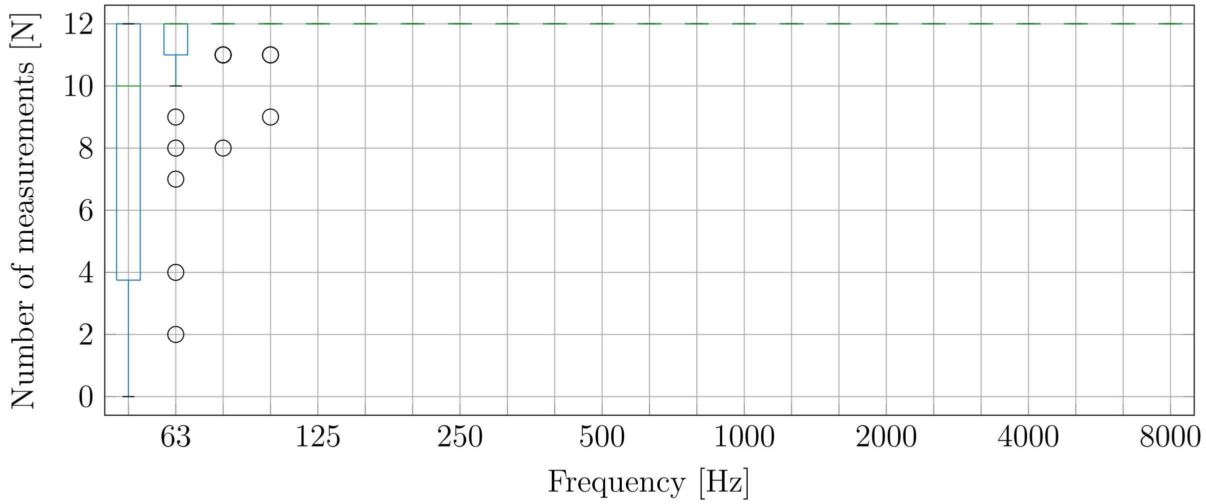


Figure M.2: Box plot of number of measurements used to obtain reverberation times.

To validate that none of the rooms measured can be categorised as rooms having very special characteristics the distribution of reverberation times (RT) for the rooms can be seen on figure M.3. The distribution from 63 Hz - 8000 Hz is deemed normal for furnished rooms.

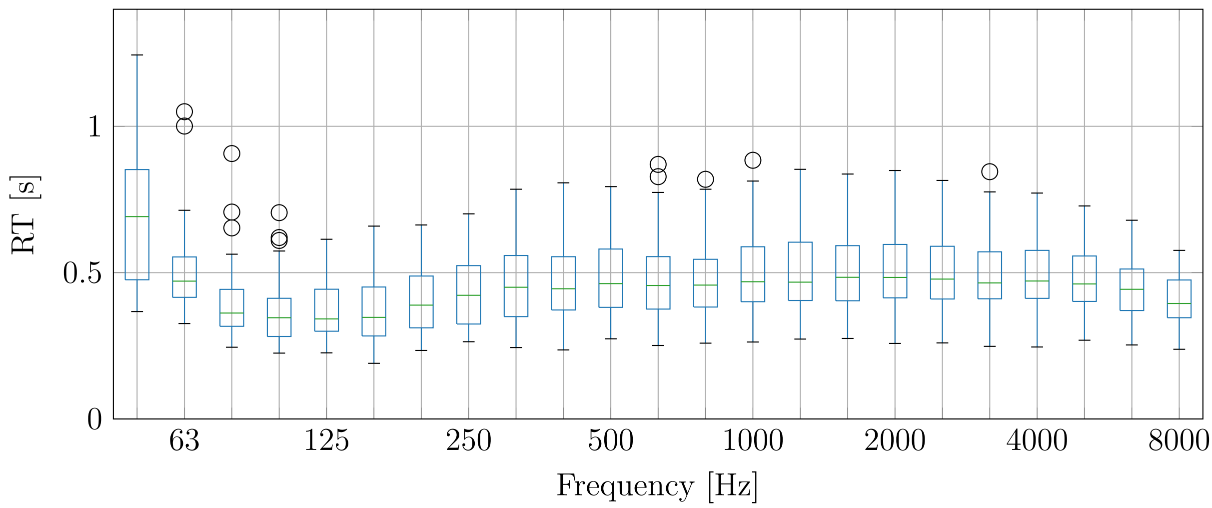
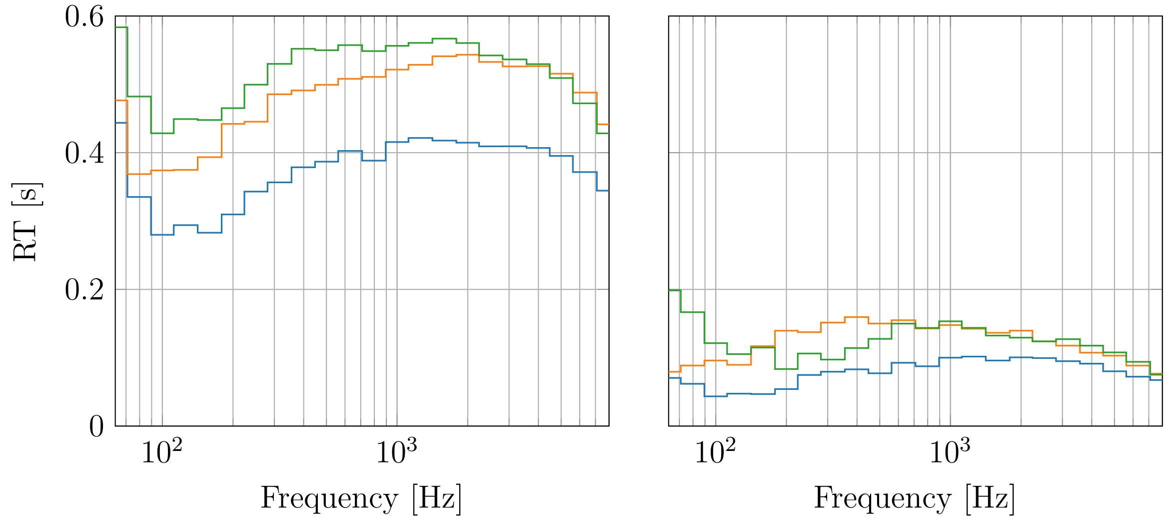


Figure M.3: Box plot of reverberation times for the entire dataset. Two outliers in the 50 Hz band (RT=2.676 s & RT= 2.686 s) are not visible.

Discarding the 50 Hz band as it is not valid for analysis it can be seen that the reverberation time increase slightly with frequency and does not decrease as stated in literature [Maekawa et al., 2010]. Taking the 50 Hz band into account the reverberation time increases drastically with a decrease in frequency which is to be expected as the wavelength becomes much larger than the room size.

M.2 | Measurements: Room Analysis

To give a better overview of the room parameters the data is split into the three rooms; living room, kitchen and bedroom. The mean and standard deviation for the reverberation time can be seen on figure M.4. As it can be seen the bedroom has the lowest reverberation (0.3 s - 0.4 s) time which is to be expected. The reverberation time of the living room (0.45 s - 0.55 s) is actually larger than the reverberation time of the kitchen (0.4 s - 0.5 s) at most frequency bands.



(a) Mean.
(b) Standard deviation.

Figure M.4: Reverberation time (RT) of bedroom (●), kitchen (●), living room (●).

The reason for the living rooms higher reverberation time can be found in the difference in volume between the rooms. The volume of the living is much larger than the volume of the kitchen and bedroom as seen on figure M.5.

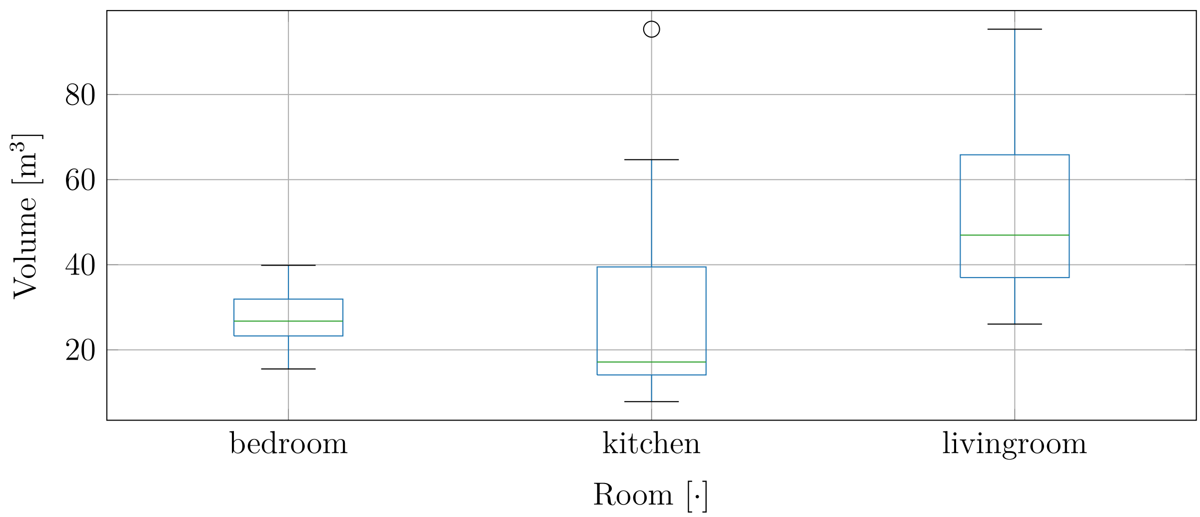
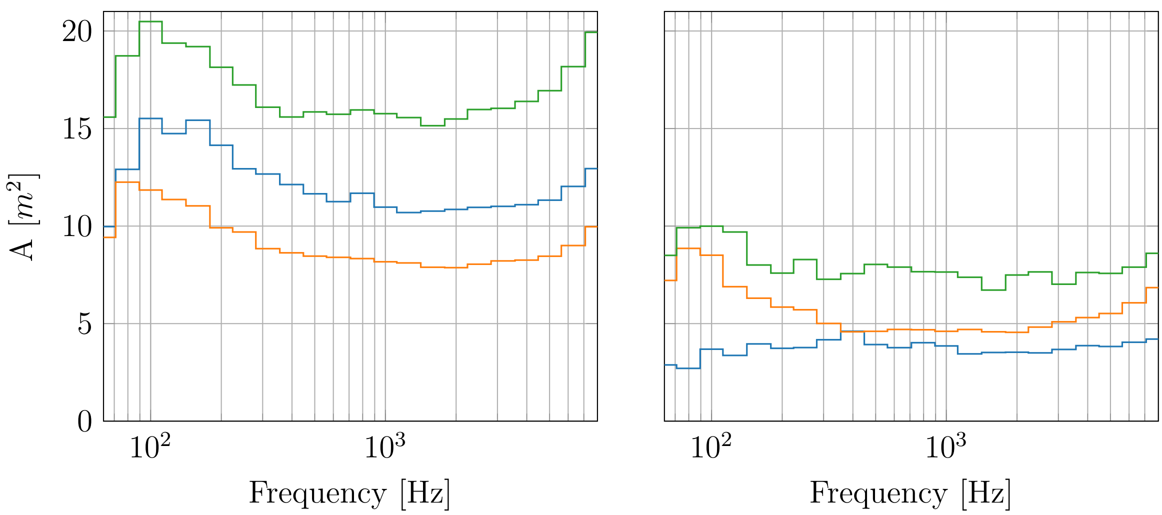


Figure M.5: Box plot of the volume distribution for the room types.

The reverberation time is however very equal at the higher frequency bands which is assumed to be because of the increase porous absorbers in the living room. The low reverberation time at the bands at 100 Hz - 200 Hz is believed to be because of membrane absorbers such as windows, cabinets ets. [Maekawa et al., 2010]. It is noted that there is a higher standard deviation at 200 Hz - 300 Hz in the kitchen which could indicate that there is larger difference in membrane absorption in kitchens than the other rooms. The dataset is however small and many kitchen were openly connected to other rooms making it difficult to conclude difference in membrane absorption with certainty.

To account for the volume of the rooms the equivalent absorption area (A) is calculated and can be seen on figure M.6. Here it is clearly seen that the kitchen has the least equivalent absorption area (8 m^2 - 11 m^2), the bedroom has the second highest equivalent absorption area (11 m^2 - 14 m^2) and the living room has the highest (15 m^2 - 17 m^2). This is in line with the volumes of the rooms and the absorption of the rooms interior. It should be noted that the volumes are based of a rectangular shape of every room even though the room was not rectangular and there could be a significant error in the volume estimation.



(a) Mean. **(b)** Standard deviation.

Figure M.6: Equivalent absorption area (A) of bedroom (●), kitchen (●), living room (●).

If the average absorption (α) is calculated as seen on figure M.7 the bedroom has the highest average absorption (0.2 - 0.25). The absorption parameter should be directly linked to how good the absorption is in a room which can be misleading for reverberation time and equivalent absorption area as these are affected by the volume of the room. It therefore makes sense that the bedroom has the highest absorption as a bed is a very large absorber.

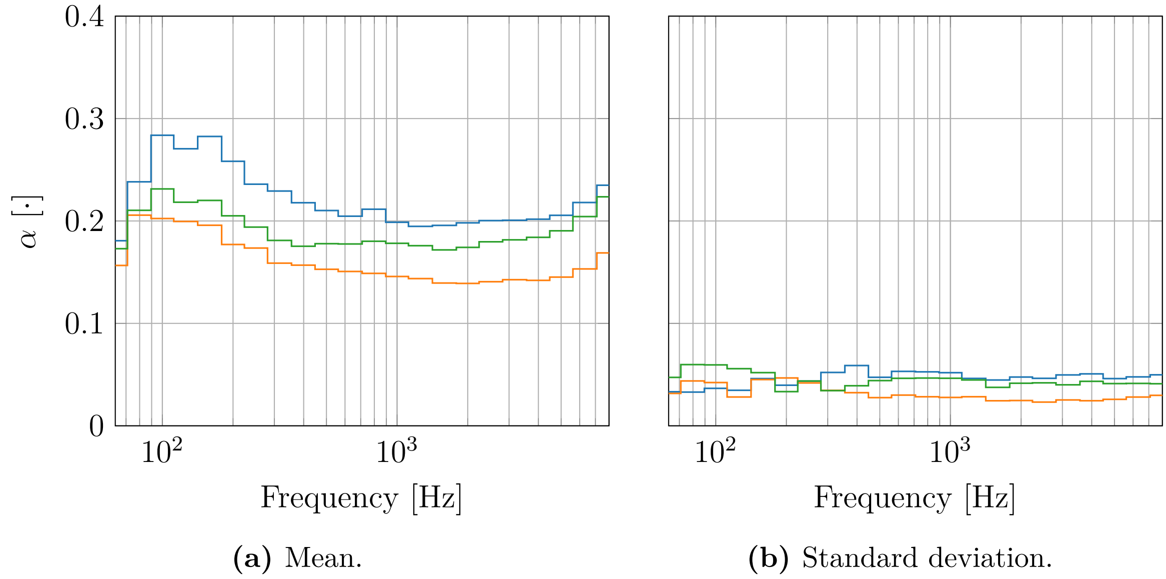


Figure M.7: Absorption (α) of bedroom (●), kitchen (●), living room (●).

The early decay time (EDT) is a little lower than the reverberation time meaning according to literature that the perceived reverberation of the rooms are lower than they actually are [ISO 3382-1, 2009].

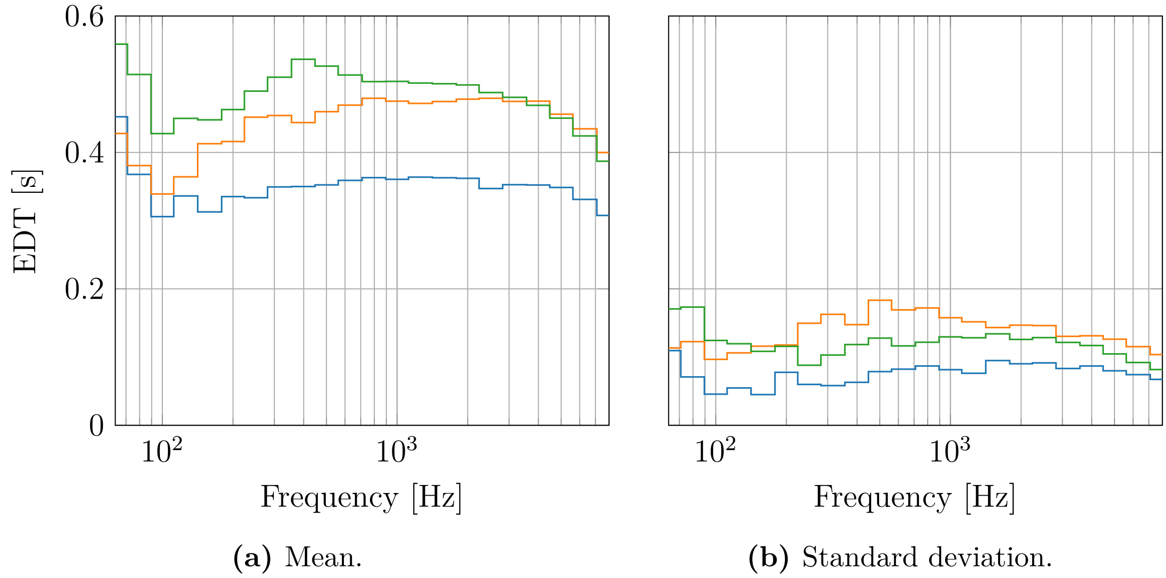
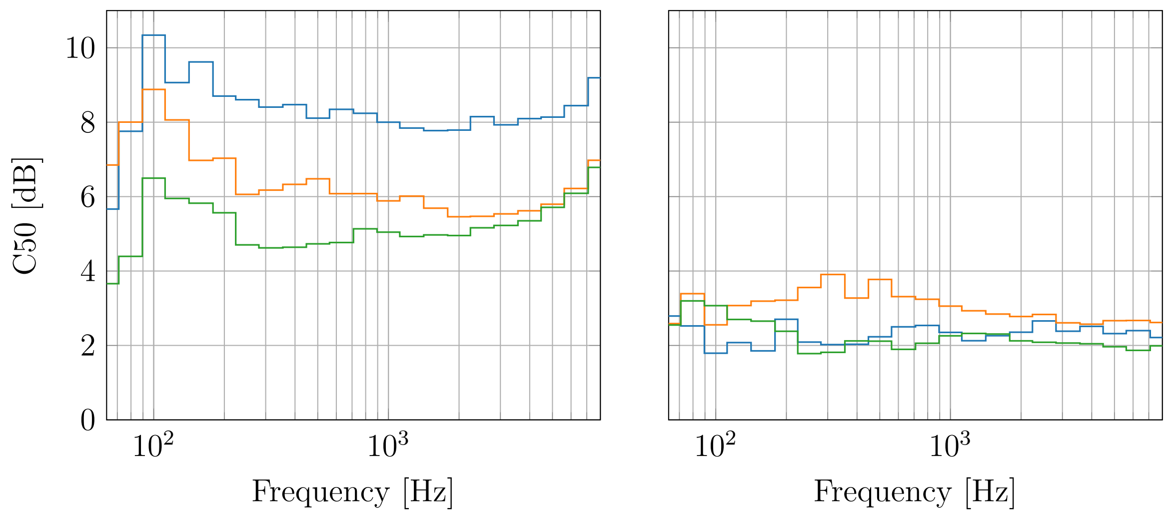


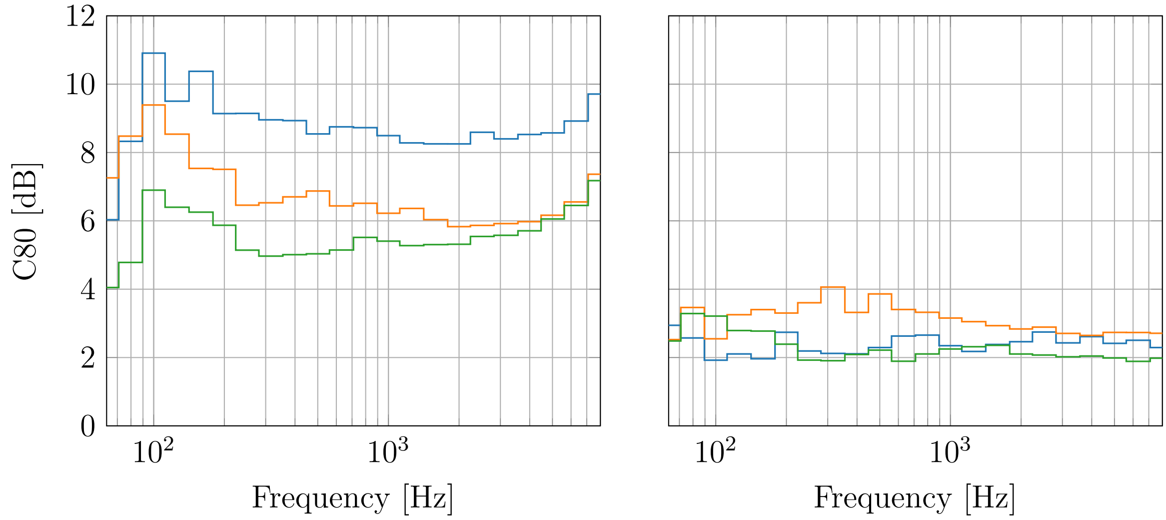
Figure M.8: Early decay time (EDT) of bedroom (●), kitchen (●), living room (●).

The clarity measures; clarity speech (C_{50}), clarity music (C_{80}), definition (D_{50}) and centre time (T_s) can be seen on figure M.9, figure M.10, figure M.11 and figure M.12 respectively. All these measures looks to correlate very well which is according to literature [Pelorson et al., 1992]. The bedroom has the highest clarity. The kitchen however has the second highest clarity which seems non-logical. It is important to reiterate that the clarity measures are normally used for performance spaces where the volume is usually much larger than in domestic rooms. This shows e.g. in C_{50} where 50 ms is used to distinguish between early reflections and late reflections. 50 ms corresponds to a travel distance of 17.1 meter, which in a domestic room equals several reflections from surfaces.



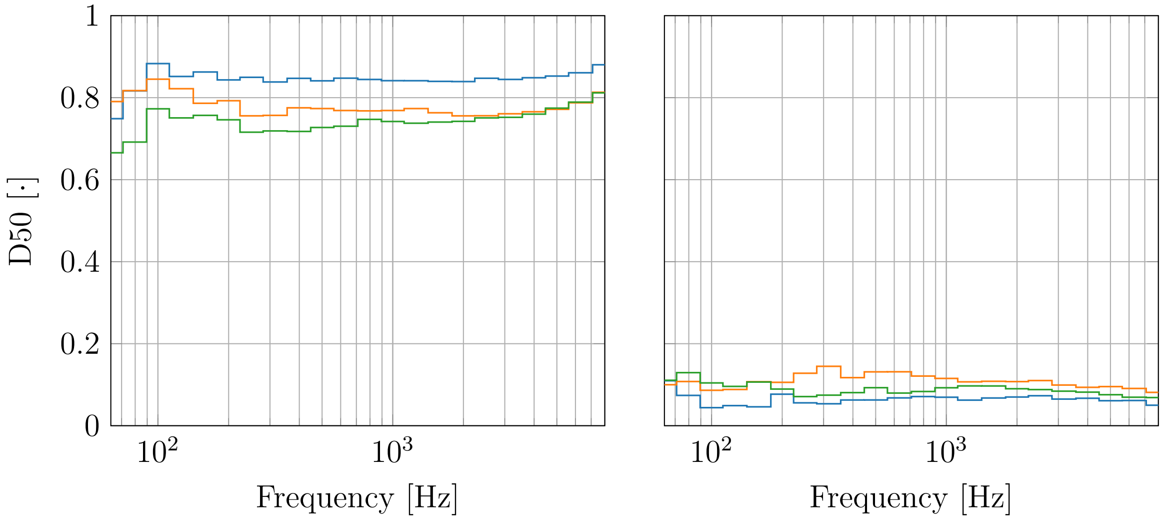
(a) Mean. **(b)** Standard deviation.

Figure M.9: Clarity speech (C_{50}) of bedroom (●), kitchen (●), living room (●).



(a) Mean. **(b)** Standard deviation.

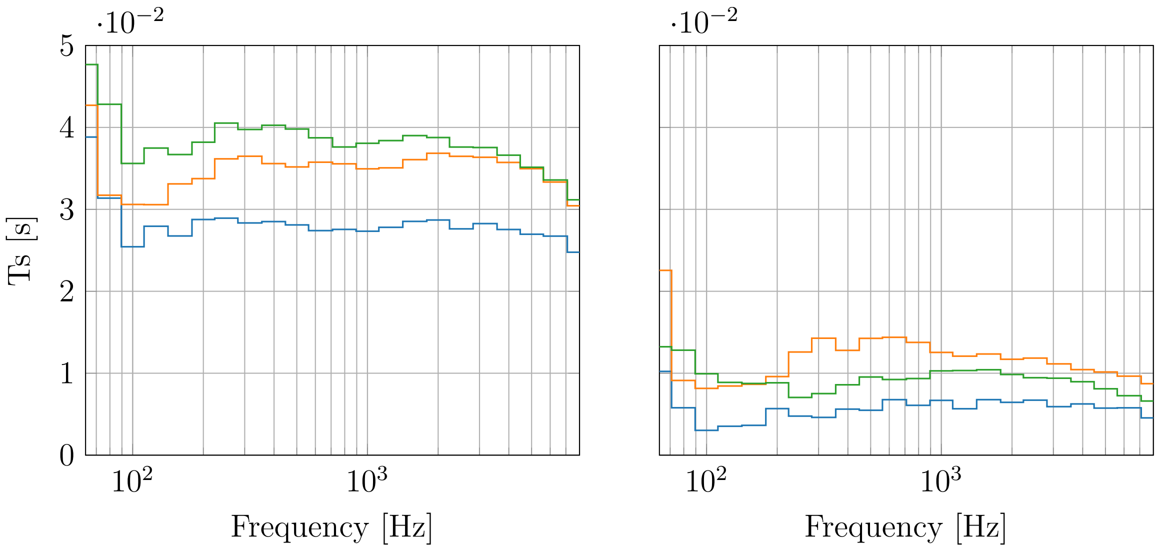
Figure M.10: Clarity music (C_{80}) of bedroom (●), kitchen (●), living room (●).



(a) Mean.

(b) Standard deviation.

Figure M.11: Definition (D_{50}) of bedroom (●), kitchen (●), living room (●).

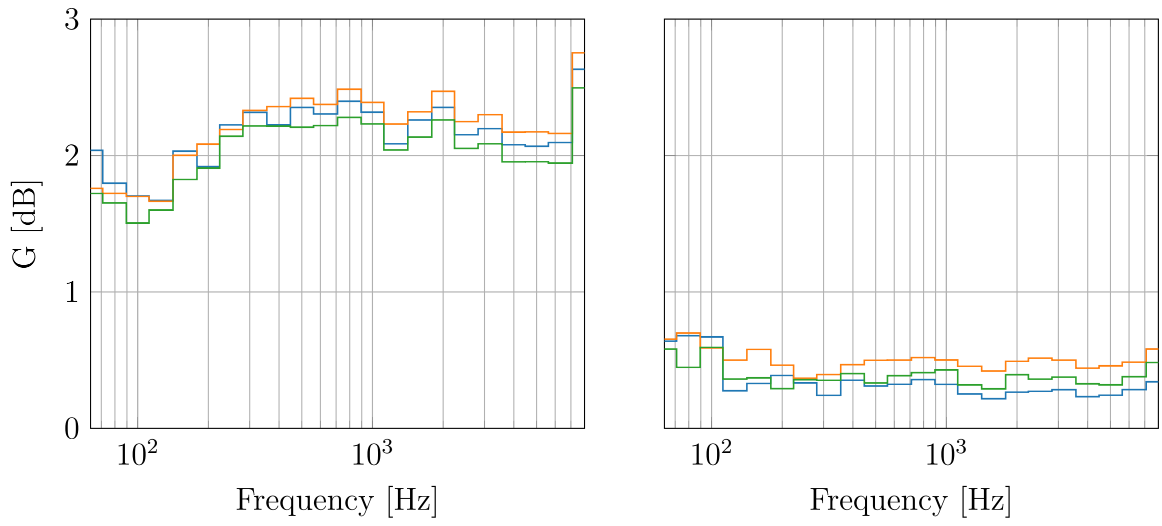


(a) Mean.

(b) Standard deviation.

Figure M.12: Centre time (T_s) of bedroom (●), kitchen (●), living room (●).

The strength (G) of the room can be seen on figure M.13. The three rooms have almost the same strength however the kitchen has the highest and the living room has the lowest. This coincides with the kitchen having a low volume and a low absorption. According to the literature strength should correlate highly with the clarity measures [Pelorson et al., 1992]. This is however probably not the case as the kitchen is the room with the second highest/lowest clarity measure which is not the case with strength.



(a) Mean. **(b)** Standard deviation.

Figure M.13: Strength (G) of bedroom (●), kitchen (●), living room (●).

The last parameters is speech transmission index (STI) which can be seen on figure M.14. The STI is calculated using the indirect method from the impulse response. It assumed that a normal speech level is 60 dB SPL. Therefore 40 dB is subtracted from the INR to more correctly represent the SNR as the SPL was approximately 100 dB during measurements. Even with a 40 dB subtraction an STI of >0.7 is obtained which should only be obtainable in recording studios [IEC 60268-16, 2011]. If the SNR has no influence on the STI then it is only reverberation time which has an affect. The bedroom has the highest STI (0.75 - 0.85) while the living room and kitchen are very equal (0.7 - 0.8).

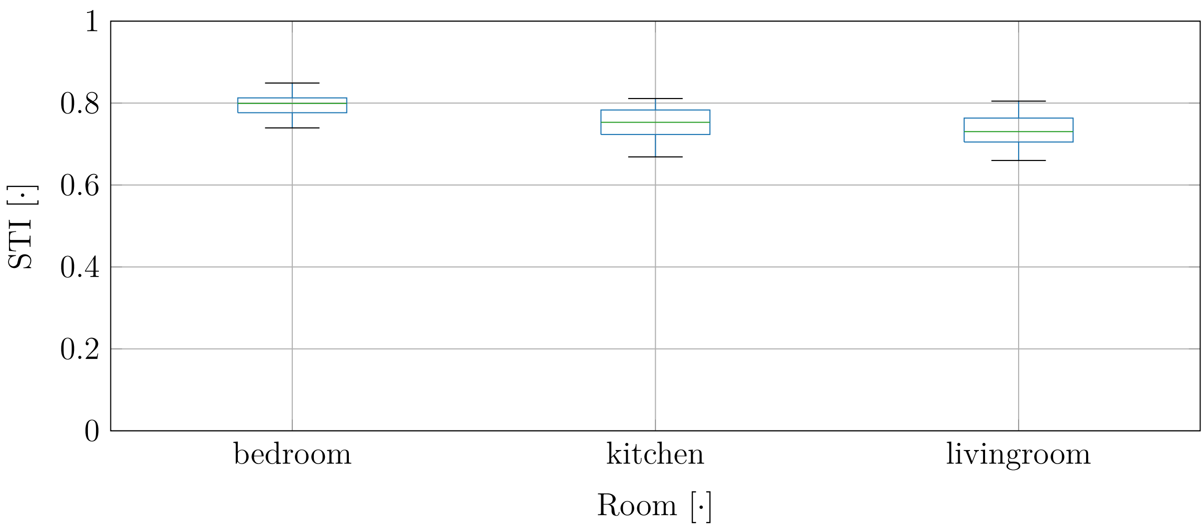


Figure M.14: Box plot of STI for the three rooms.

All the different parameters have now been presented. It is however desired to reduce the number of dimensions as it is known that many of the parameters are correlated in performance spaces.

M.3 | Measurements: Factor Analysis

From the parameter analysis it could be seen that many of the parameters seemed to correlate. In order to understand how many dimensions there are and what the underlying factors are, an exploratory factor analysis (EFA) will be performed. There are six basic steps to performing an EFA which will be followed [DeCoster, 1998]:

1. Obtain the correlation matrix.
2. Select the number of factors for inclusion.
3. Extract your initial set of factors.
4. Rotate your factors to a final solution.
5. Interpret your factor structure.
6. Construct factor scores for further analysis.

The correlation matrix for the parameters can be seen on table M.1. If any variable does not correlate higher than 0.3 with any other it is removed. This is however not the case.

	RT	A	α	EDT	C_{50}	C_{80}	D_{50}	T_s	G	STI
RT	**1.00**	0.37	-0.64	0.95	-0.92	-0.93	-0.93	0.93	-0.16	-0.99
A	0.37	**1.00**	0.43	0.50	-0.51	-0.50	-0.54	0.54	-0.53	-0.33
α	-0.64	0.43	**1.00**	-0.49	0.47	0.47	0.44	-0.43	-0.28	0.67
EDT	0.95	0.50	-0.49	**1.00**	-0.98	-0.98	-0.99	0.99	-0.19	-0.94
C_{50}	-0.92	-0.51	0.47	-0.98	**1.00**	**1.00**	0.99	-0.98	0.17	0.92
C_{80}	-0.93	-0.50	0.47	-0.98	**1.00**	**1.00**	0.99	-0.98	0.18	0.93
D_{50}	-0.93	-0.54	0.44	-0.99	0.99	0.99	**1.00**	**-1.00**	0.21	0.92
T_s	0.93	0.54	-0.43	0.99	-0.98	-0.98	**-1.00**	**1.00**	-0.20	-0.91
G	-0.16	-0.53	-0.28	-0.19	0.17	0.18	0.21	-0.20	**1.00**	0.13
STI	-0.99	-0.33	0.67	-0.94	0.92	0.93	0.92	-0.91	0.13	**1.00**

Table M.1: Correlation Matrix for the parameters.

For selecting the number of relevant factors the Kaiser-Criterion is used. This states that the number of eigenvalues above 1 for the correlation matrix should be the number of factors for inclusion [Kaiser, 1960]. The scree plot can be seen in figure M.15 which shows two eigenvalues above 1.

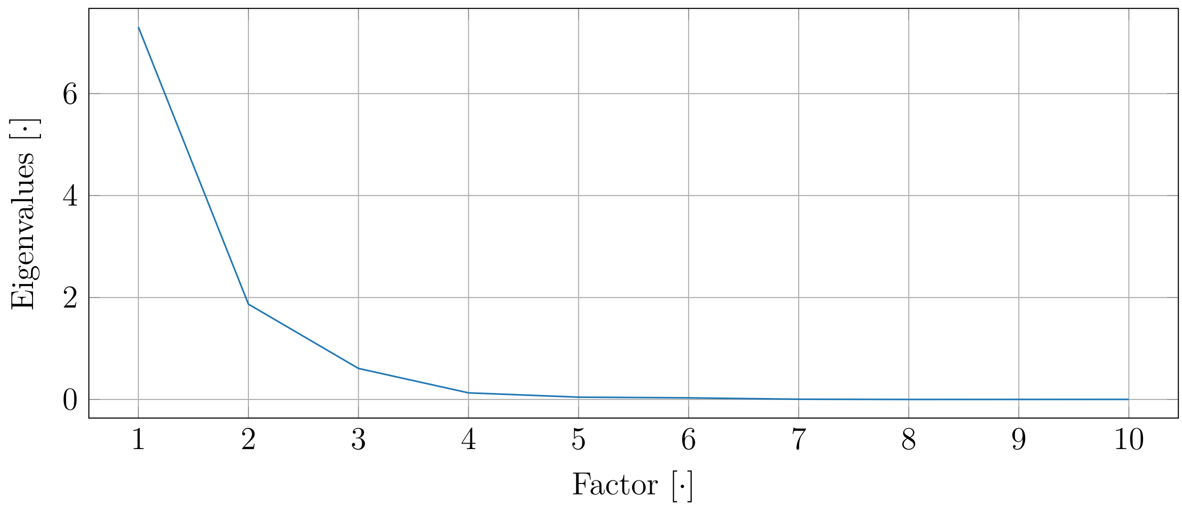


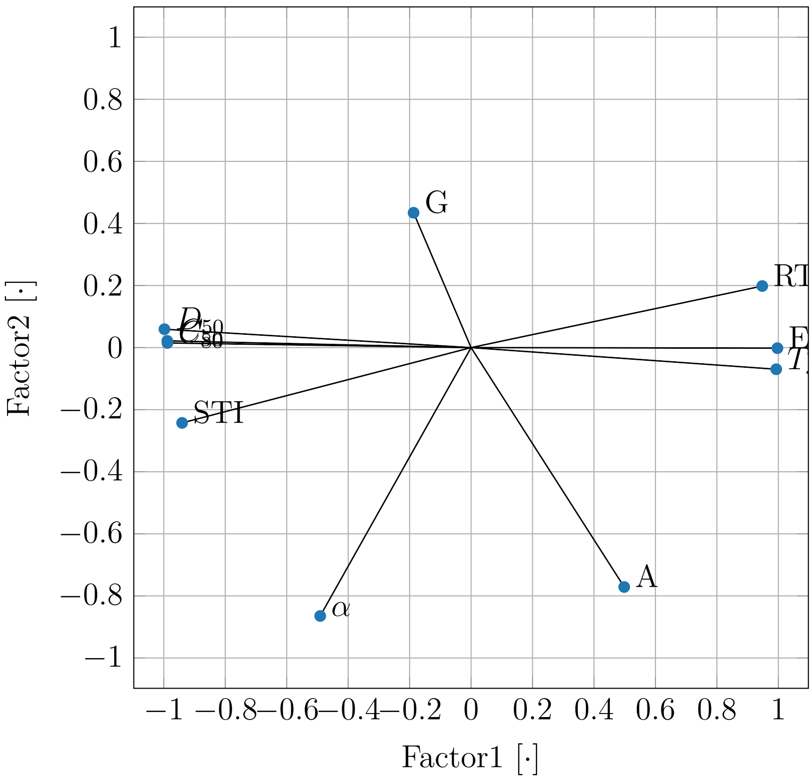
Figure M.15: Scree plot.

A rotation is used to simplify the complexity of the factors. The rotation used is VARIMAX which is the most common rotation used in factor analysis [Tabachnick and Fidell, 2012]. The rotation did almost not rotate the loadings so the non-rotated loadings are not shown. The rotated loadings of the calculated components can be seen on figure M.16. A loading is set to be a contribution to a factor if the loading is above 0.5. An explanation for each factor is given below. It should also be noted that a room sample was removed because it was an outlier.

Factor 1 is based on RT, EDT, T_s, STI, C_{50}, C_{80} and D_{50}. The factor can therefore clearly be interpreted as the reverberation. This coincides well with the room analysis.

Factor 2 is based on A, α. The factor is therefore interpreted as the absorption as both parameters describe the absorption in a room.

The scores for the different samples can be seen on figure M.17. Here it can be seen that most kitchen are low on factor 2 as these have a low absorption while the distribution of rooms on factor 1 are more uniform as volume has a large influence on reverberation as determined in the room analysis.



	Factor 1 (72.37%)	Factor 2 (16.38%)
RT	**0.95**	0.20
A	**0.50**	**-0.77**
α	-0.49	**-0.86**
EDT	**1.00**	-0.00
C50	**-0.99**	0.02
C80	**-0.99**	0.01
D50	**-1.00**	0.06
Ts	**0.99**	-0.07
G	-0.19	0.43
STI	**-0.94**	-0.24

(a) Loadings plot **(b)** Loadings Matrix

Figure M.16: Loadings from principal component analysis

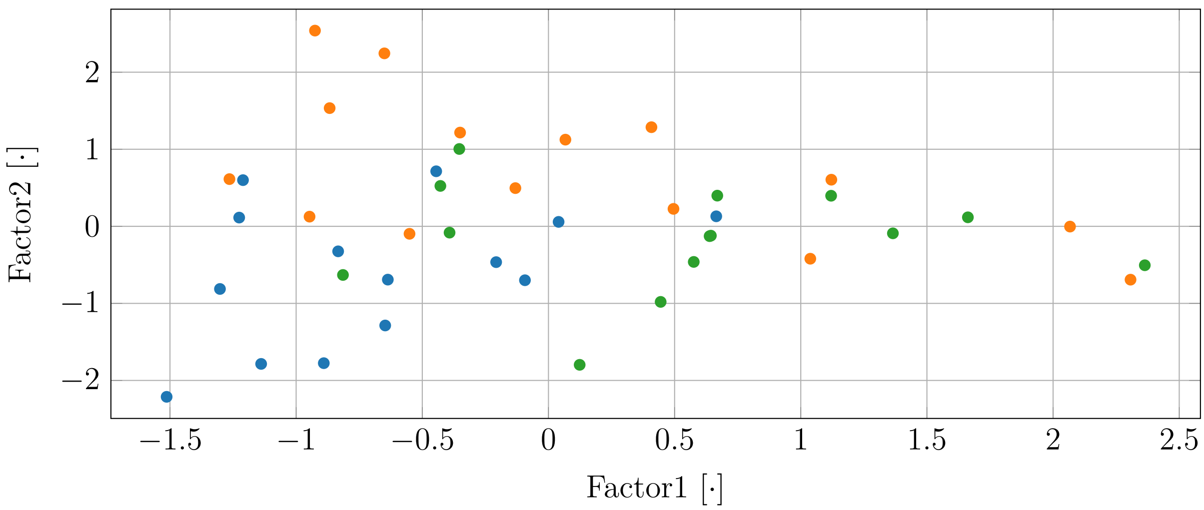
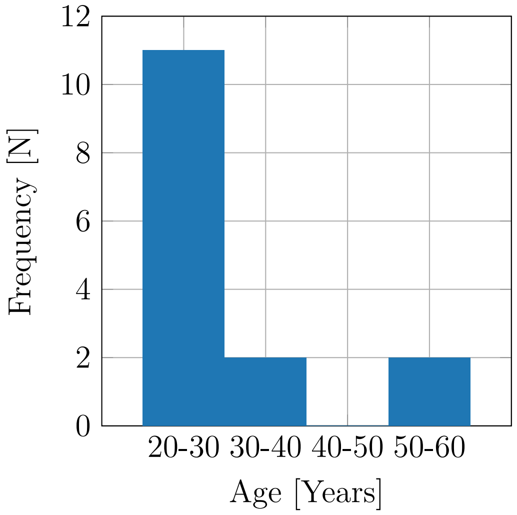


Figure M.17: Score plot. The rooms are bedroom (●), kitchen (●), living room (●).

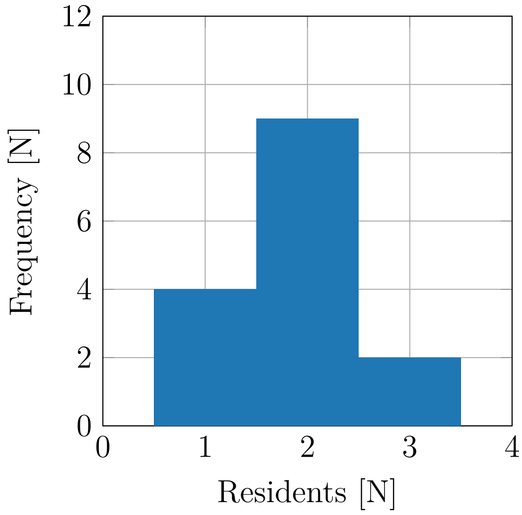
This concludes the analysis of room parameters and the questionnaire data will now be analysed.

M.4 | Questionnaire: Data

One resident from every dwelling responded to the questionnaire totaling 15 answered questionnaires. Each questionnaire contains 82 answers based on 38 categories. The full questionnaire can be found in Appendix K. A histogram of every segment is presented to show the distribution of answers. The population consists of 4 females and 11 males in the age between 23 - 54 years old as seen on figure M.18. No respondent had any known hearing disorders. Two respondent have lived outside Denmark in 1 year and 29 years respectively. All but 3 respondents have lived in their dwelling between 1-5 years while the other three have lived in their respective dwelling for +5 years. The number of residents can be seen on figure M.18. Only one respondent had kids under 13 years old.



(a) The distribution of age



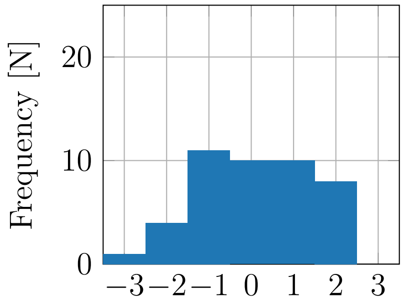
(b) The distribution of number of residents.

Figure M.18: Personal information distributions.

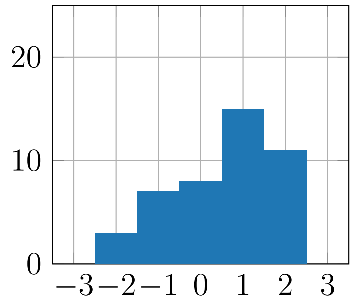
The answers to the question *The room influences sound so it feels?* (sound segment) can be seen on figure M.19 and the answers to the question *When I am in the room I feel?* (comfort segment) can be seen on figure M.20. Because both categories were used to ask about both for living room, kitchen and bedroom a total of 45 answers were gathered for the two categories respectively.

In general two kinds of distributions can be seen from the answers. Most of them show signs of a normal distribution, some however seems to have half a normal distribution. All distributions in the sound segment looks normal distributed. The scales which does not look normal distributed are: sad/happy and uneasy/calm. A distribution such as uncomfortable/comfortable from the comfort segment could be from either distribution.

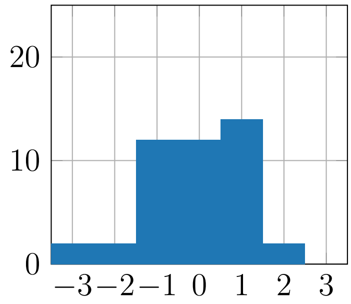
Analysing the scales it can be seen that most of the categories are used when the respondents have answered meaning the scales are designed properly. A last thing to note is that 2 scales are the same in the sound and comfort segment. The answers however are not identical.



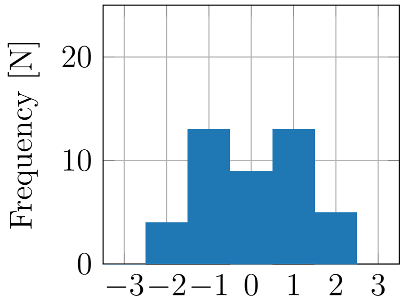
(a) Dead/Resounding



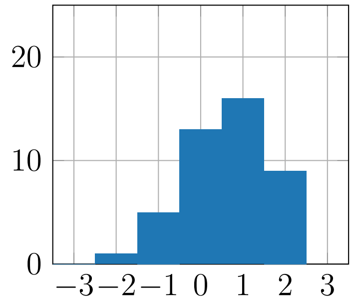
(b) Unclear/Clear



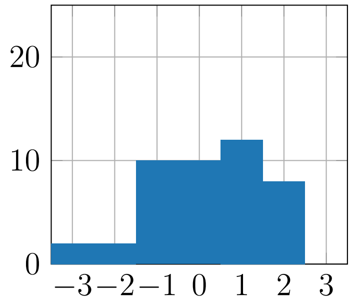
(c) Compact/Spacious



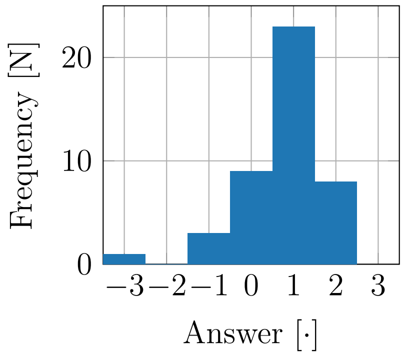
(d) Quiet/Noisy



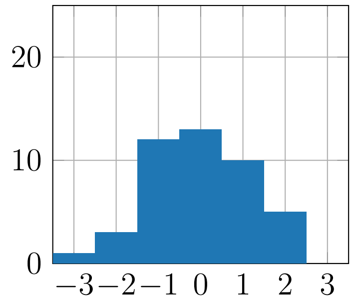
(e) Uncomfortable/Comfortable



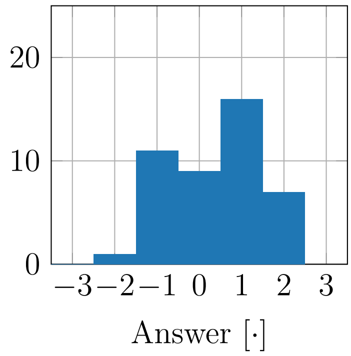
(f) Attenuated/Amplified



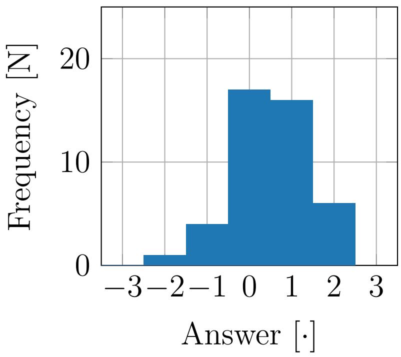
(g) Remote/Enveloping



(h) Soft/Hard

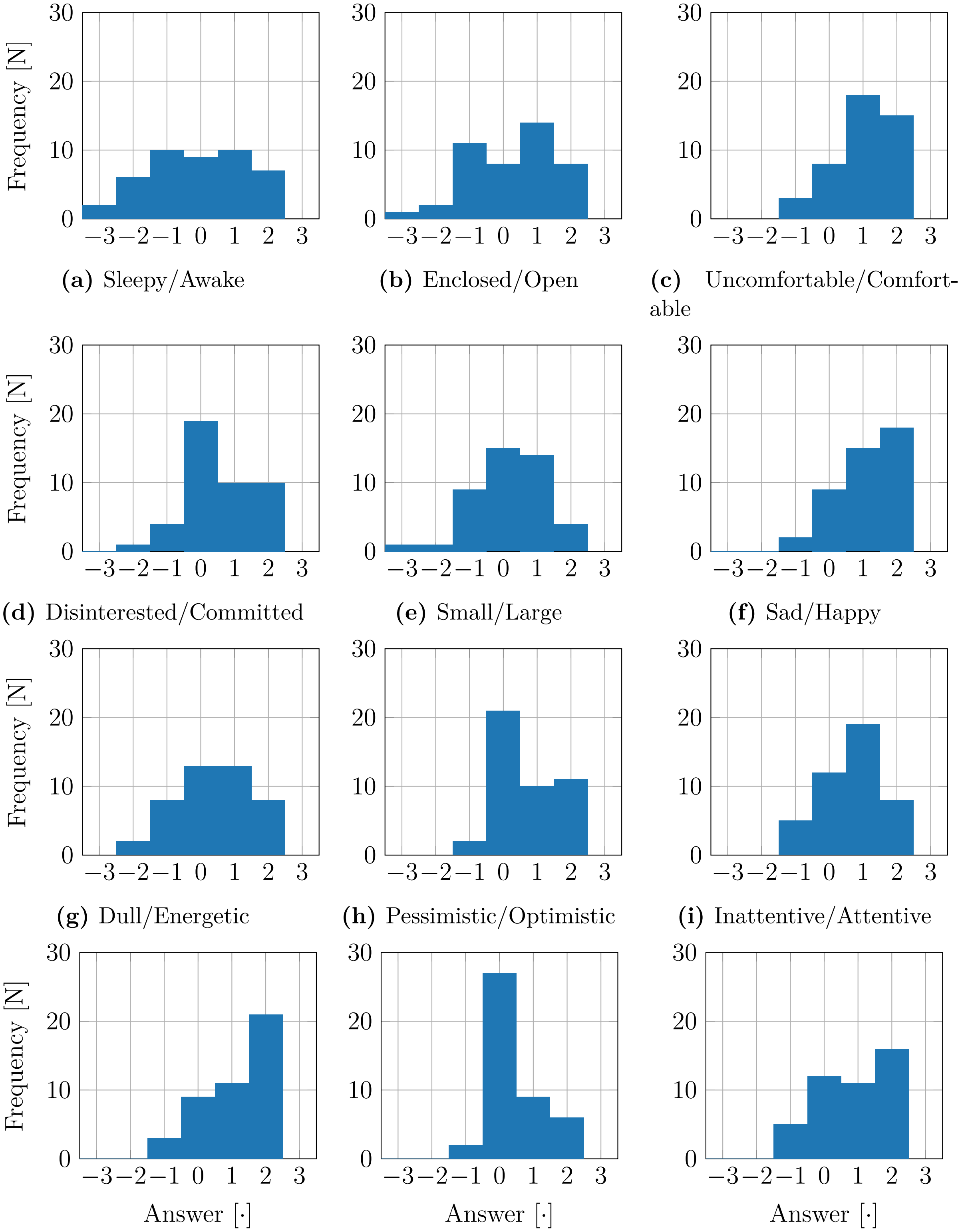


(i) Uneasy/Calm



(j) Absent/Present

Figure M.19: Histogram of questionnaire answers for the sound segment.



(a) Sleepy/Awake **(b)** Enclosed/Open **(c)** Uncomfortable/Comfortable

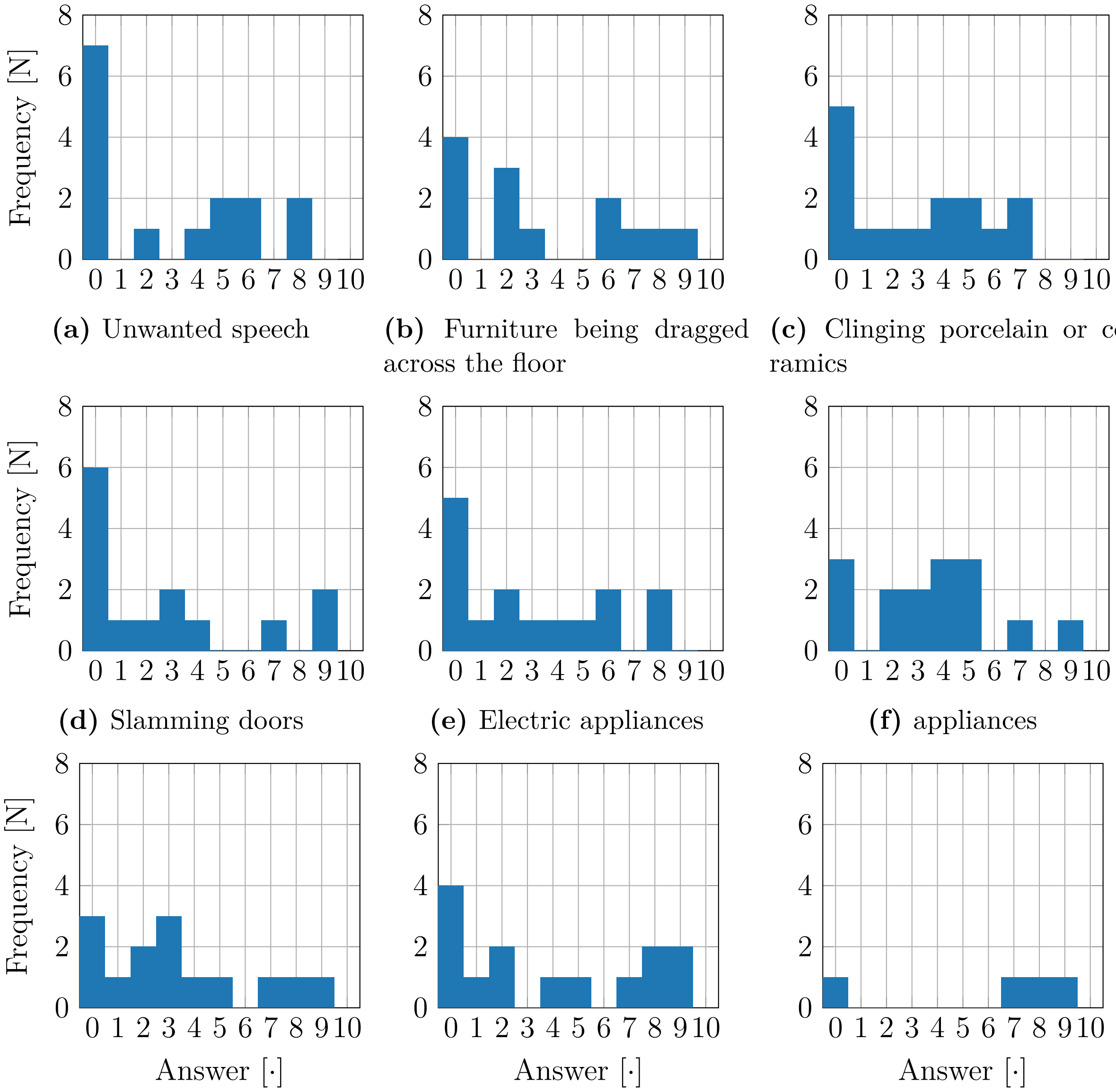
(d) Disinterested/Committed **(e)** Small/Large **(f)** Sad/Happy

(g) Dull/Energetic **(h)** Pessimistic/Optimistic **(i)** Inattentive/Attentive

(j) Uneasy/Calm **(k)** Dispirited/Lively **(l)** Stressed/Relaxed

Figure M.20: Histogram of questionnaire answers for the comfort segment.

The noise segment asked *how much does noise from inside your dwelling bother, disturb or annoy you?*. The answers can be seen on figure M.21. There are clearly not enough answers (15 per scale) to see a distribution. It does however look as some of the scale has a majority of the answers in 0 or close to zero while a few of the answers are higher on the scale. The other noise scale has been answered 3 times which is interpreted as the scales designed cover the majority of noise sources. The noise sources mentioned in the other sources are neighbours, floor creaking and nothing stated.



(a) Unwanted speech **(b)** Furniture being dragged across the floor **(c)** Clinging porcelain or ceramics

(d) Slamming doors **(e)** Electric appliances **(f)** appliances

(g) Kitchen tools **(h)** Technical installations **(i)** Other noise

Figure M.21: Histogram of questionnaire answers for the noise segment.

The satisfaction segment asked *how satisfied are you with the rooms influence on sound?*. The answers can be seen on figure M.22. The distribution is difficult to interpret because of the small data set. Two different distributions could be considered. One is a normal distribution with a mean around 6 or another being two normal distributions around 5 and 7. This will be analysed further later on. What can be concluded from the answers is that not many respondents are dissatisfied with the room acoustics, but many are neither very satisfied.

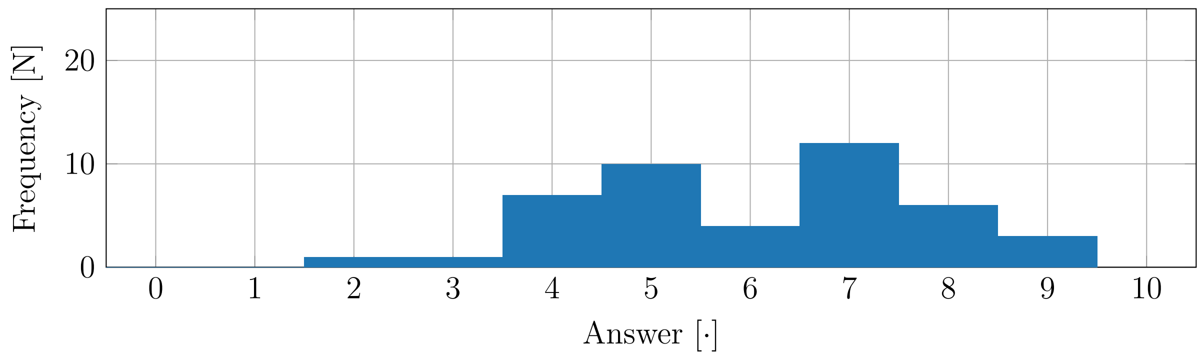
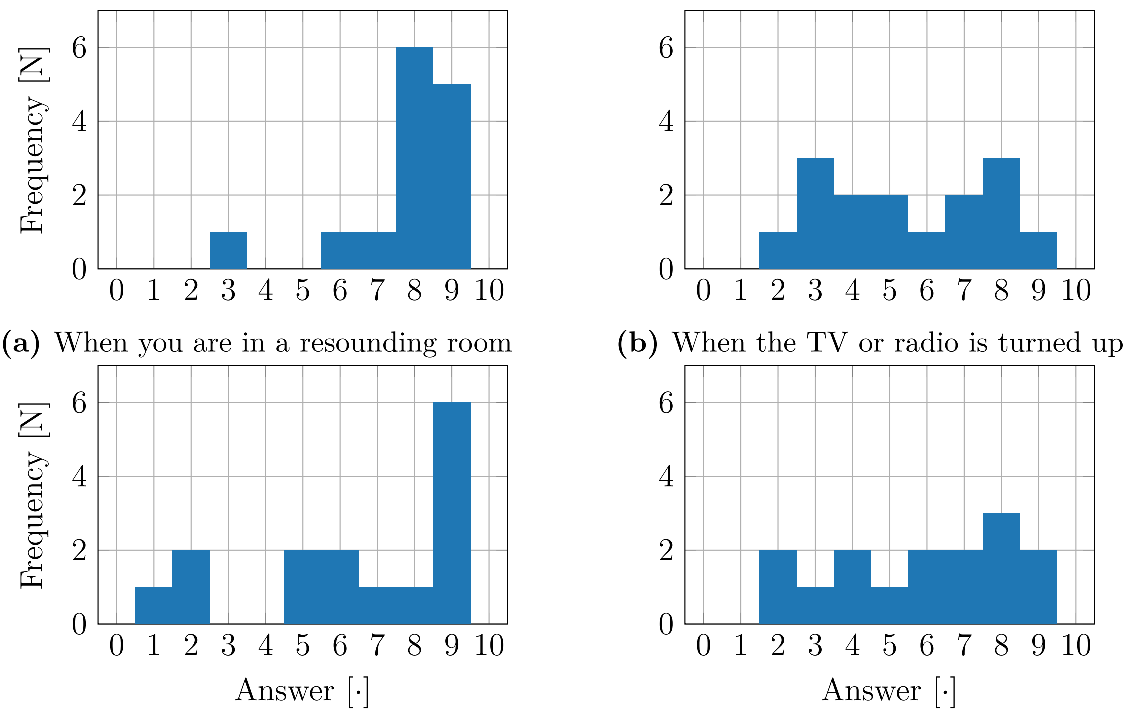


Figure M.22: Histogram of questionnaire answers for the satisfaction segment.

The last segment, the sensitivity segment asked *how much would you feel bothered, disturbed or annoyed in the following scenario?*. The answers for the different scales can be seen on figure M.23. As with the noise segment the distribution for the scales in the sensitivity segment are very difficult to interpret. Scale (a) and (c) seems to be almost extremely annoying for the majority of respondents while scale (b) and (d) looks more uniformly distributed.



(a) When you are in a resounding room

(b) When the TV or radio is turned up

(c) When the neighbour is having a party

(d) hen a lot of people talk at the same time

Figure M.23: Histogram of questionnaire answers for the sensitivity segment.

All raw data from the questionnaire have now been presented. A more in depth analysis of the different rooms will now be described.

M.5 | Questionnaire: Room Analysis

The sound segment was answered for both bedroom, kitchen and living room. A mean for every scale for every room can be seen on figure M.24. From the scales some tendencies can be seen. There are for most scales a clear distinction between the three rooms, or at least between the kitchen and the two other rooms. This aligns well with the thought of the living room and bedroom being more similar than e.g. the kitchen and bedroom. The sound segment should be one of the main focus areas as these ask directly for the rooms influence on sound. It is however difficult to give a detailed explanation of the results without knowing the underlying factors.

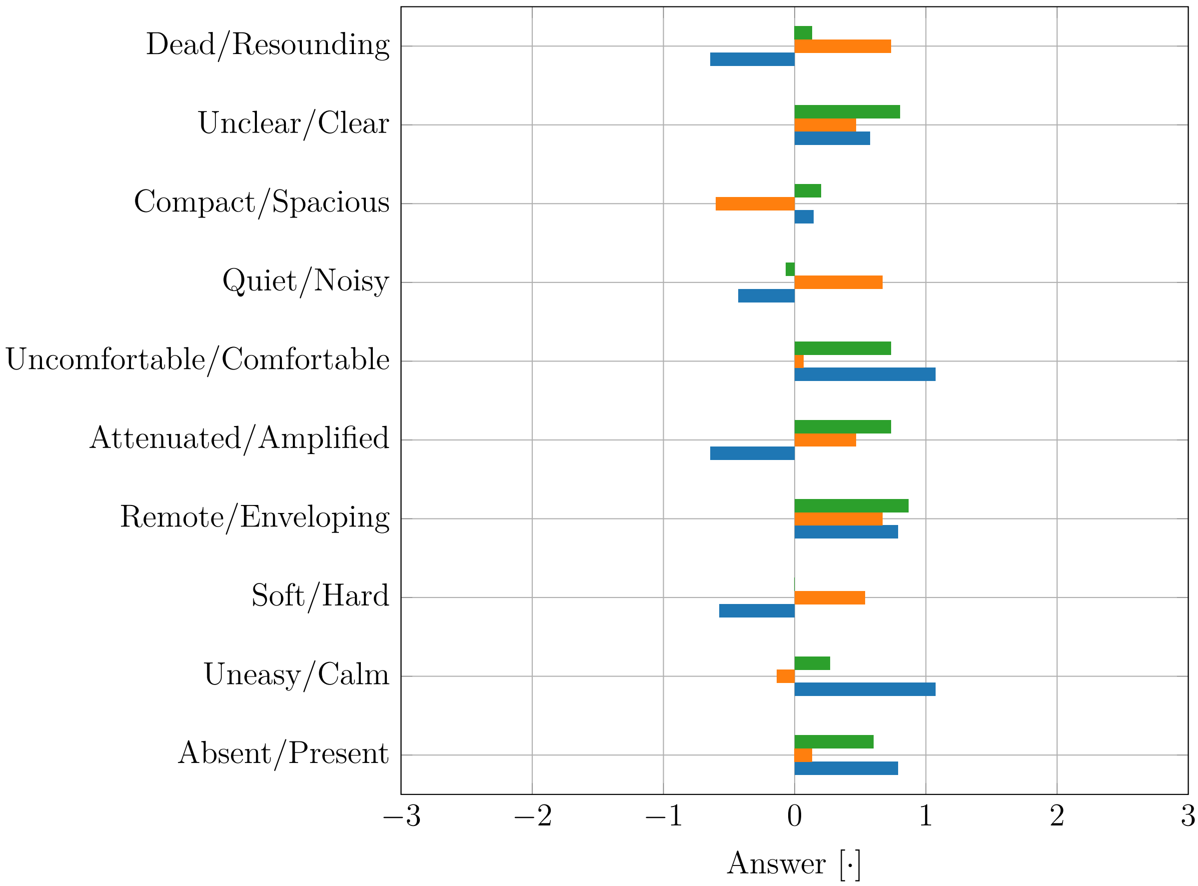


Figure M.24: Bar plot of the mean answer from all respondents in the sound segment. The rooms are bedroom (●), kitchen (●), living room (●).

As for the sound segment the mean answers to the comfort segment scales can be seen on figure M.25. Some of the scales show clear sign of the function of the room with e.g. respondents feeling much more sleepy in the bedroom than in the kitchen. The question however is if this comfort is influenced by the room? The comfort segment is therefore seen as a secondary focus areas as the segment can help identify the purpose of the room and if this has influence on comfort.

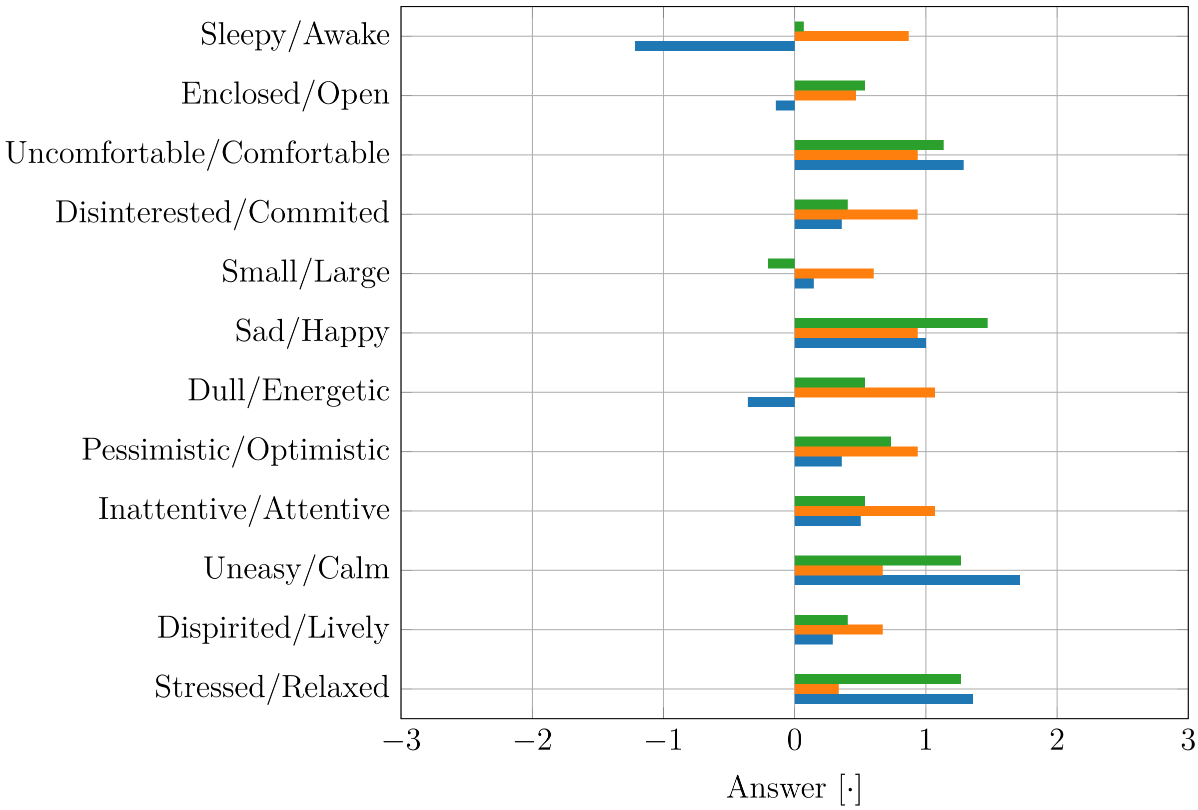
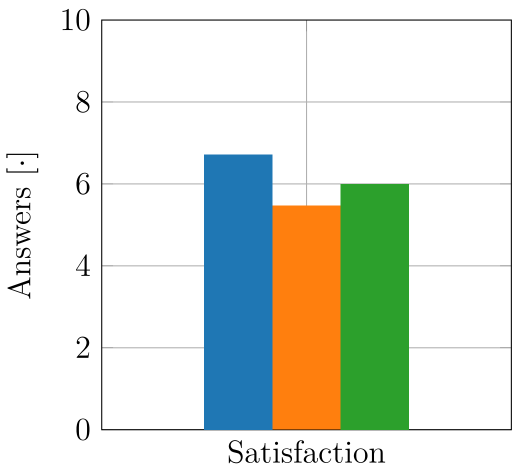
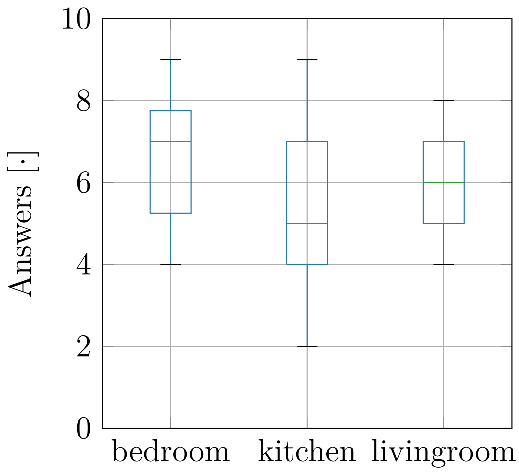


Figure M.25: Bar plot of the mean answer from all respondents in the comfort segment. The rooms are bedroom (●), kitchen (●), living room (●).

The satisfaction segment shows that people selects the bedroom as the most satisfying room acoustically as seen on figure M.26. It can also be seen that the reason for the kitchen being lower than the two other rooms is that some people are unsatisfied with the acoustics in the kitchen which results in a larger spread.



(a) Mean.



(b) Box plot.

Figure M.26: Satisfaction segment answers. The rooms are bedroom (●), kitchen (●), living room (●).

For the bedroom and living room all respondents are either satisfied or around neither satisfied or unsatisfied. Because the dataset is small it is difficult to prove if bedrooms are liked more than living rooms. As the other categories does not ask about all three rooms but about the dwelling overall they have been omitted from this section.

M.6 | Questionnaire: Factor Analysis

Because it is not known how many dimensions the sound segment and the comfort segment have further analysis must be done in order to understand how many dimensions there are and what they are the EFA will be performed again on both segments. The correlation matrix for the sound segment can be seen on table M.2.

	Dead/Resounding	Unclear/Clear	Compact/Spacious	Quiet/Noisy	Uncomfortable/Comfortable	Attenuated/Amplified	Remote/Enveloping	Soft/Hard	Uneasy/Calm	Absent/Present
Dead/Resounding	**1.00**	-0.13	-0.05	0.60	-0.41	0.61	0.09	0.41	-0.43	-0.36
Unclear/Clear	-0.13	**1.00**	0.18	0.04	0.34	-0.02	0.52	-0.16	-0.02	0.27
Compact/Spacious	-0.05	0.18	**1.00**	-0.10	0.47	-0.08	0.07	-0.36	0.30	0.08
Quiet/Noisy	0.60	0.04	-0.10	**1.00**	-0.21	0.51	0.12	0.24	-0.32	-0.38
Uncomfortable/Comfortable	-0.41	0.34	0.47	-0.21	**1.00**	-0.14	0.12	-0.53	0.58	0.54
Attenuated/Amplified	0.61	-0.02	-0.08	0.51	-0.14	**1.00**	0.27	0.40	-0.35	-0.09
Remote/Enveloping	0.09	0.52	0.07	0.12	0.12	0.27	**1.00**	-0.08	-0.02	0.43
Soft/Hard	0.41	-0.16	-0.36	0.24	-0.53	0.40	-0.08	**1.00**	-0.72	-0.28
Uneasy/Calm	-0.43	-0.02	0.30	-0.32	0.58	-0.35	-0.02	-0.72	**1.00**	0.42
Absent/Present	-0.36	0.27	0.08	-0.38	0.54	-0.09	0.43	-0.28	0.42	**1.00**

Table M.2: Correlation Matrix for the sound category

The scree plot can be seen in figure M.27 which shows three eigenvalues above 1.

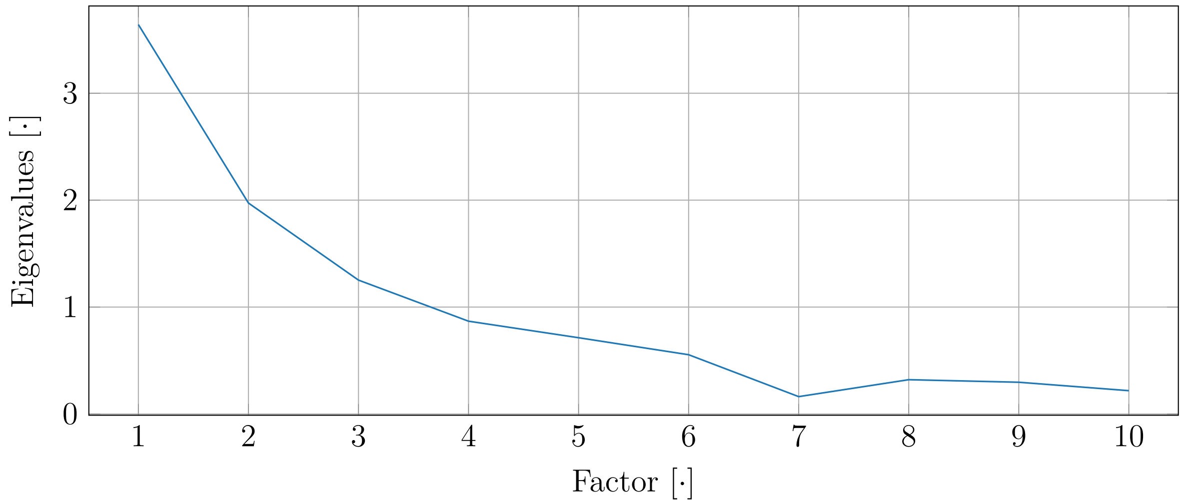


Figure M.27: Scree plot for the sound segment.

Using 3 factors the non-rotated and rotated loadings can be seen in table M.3. One outlier was removed.

	Factor 1 (43.67%)	Factor 2 (17.68%)	Factor 3 (10.60%)
Dead/Resounding	**-0.96**	0.39	0.44
Unclear/Clear	0.23	**0.62**	-0.43
Compact/Spacious	0.36	0.25	0.27
Quiet/Noisy	**-0.69**	0.40	0.40
Uncomfortable/Comfortable	**0.64**	0.31	0.08
Attenuated/Amplified	**-0.73**	**0.62**	0.17
Remote/Enveloping	0.03	**0.60**	-0.26
Soft/Hard	**-0.92**	-0.15	-0.36
Uneasy/Calm	**0.87**	0.07	0.38
Absent/Present	0.49	0.36	-0.26

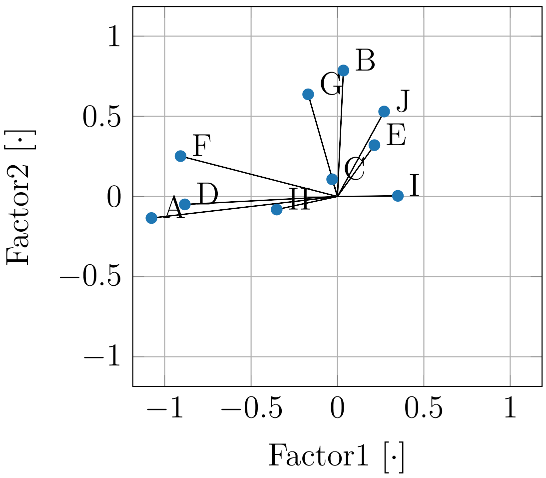
(a) Loading matrix

	Factor 1 (31.61%)	Factor 2 (15.08%)	Factor 3 (25.26%)
Dead/Resounding	**-1.08**	-0.13	-0.29
Unclear/Clear	0.03	**0.79**	0.08
Compact/Spacious	-0.03	0.11	**0.50**
Quiet/Noisy	**-0.88**	-0.05	-0.13
Uncomfortable/Comfortable	0.21	0.32	**0.60**
Attenuated/Amplified	**-0.91**	0.25	-0.24
Remote/Enveloping	-0.17	**0.64**	0.03
Soft/Hard	-0.35	-0.08	**-0.94**
Uneasy/Calm	0.35	0.00	**0.89**
Absent/Present	0.27	**0.53**	0.29

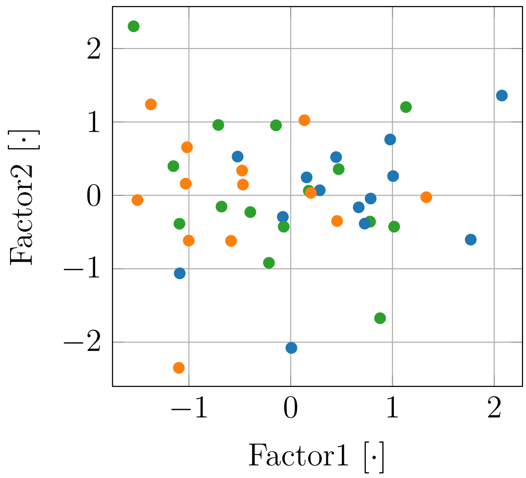
(b) Rotated loading matrix

Table M.3: Loading matrix from the factor analysis result on sound

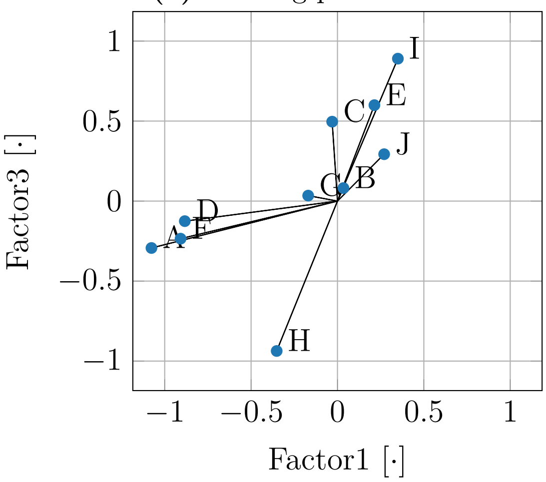
The loadings and score plots can be seen on figure M.28. No standardization or mean centering has been applied as the scale are all the same and the absolute scores are wanted to possibly distinguish between rooms. The interpretation of each factor can be seen below the figure.



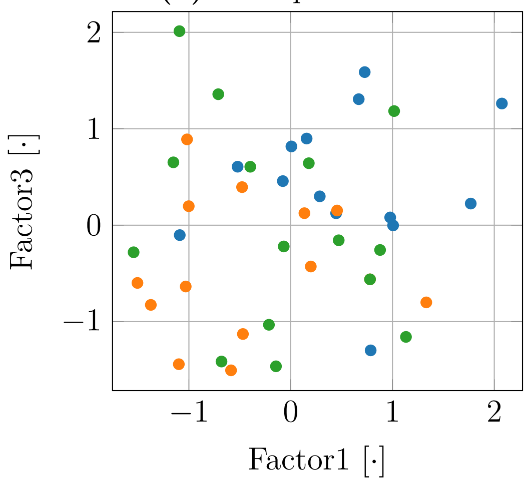
(a) Loading plot.



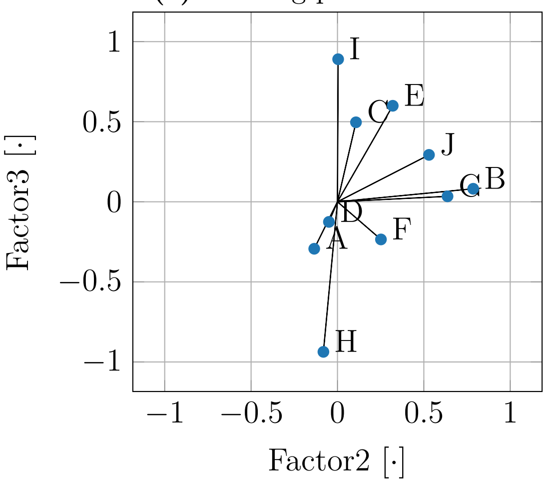
(b) Score plot.



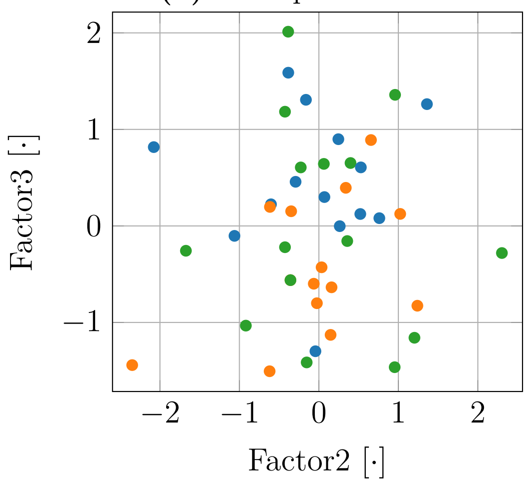
(c) Loading plot.



(d) Score plot.



(e) Loading plot.



(f) Score plot.

Figure M.28: Loading and score plot for the sound segment. The scales are denoted Dead/Resounding (A), Unclear/Clear (B), Compact/Spacious (C), Quiet/Noisy (D), Uncomfortable/Comfortable (E), Attenuated/Amplified (F), Remote/Enveloping (G), Soft/Hard (H), Uneasy/Calm (I) and Absent/Present (J). The rooms are bedroom (●), kitchen (●), living room (●).

Factor 1 is based on dead/resounding, quiet/noisy and attenuated/amplified. This is interpreted as the subjective feeling of reverberation in a room. From the score plot it can be seen that most of the kitchen are divided into one end of the factor while living rooms and bedrooms are in the other.

Factor 2 is based on unclear/clear, remote/enveloping and absent/present. Absent/present has a low loading and could be discarded. The factor is interpreted as the subjective feeling of spaciousness. From the score plot a clear trend cannot be seen between the scores and further analysis is need.

Factor 3 is based on soft/hard, uneasy/calm, uncomfortable/comfortable and compact/spacious. uncomfortable/comfortable and compact/spacious could be discarded because of a low loading. The factor is interpreted as the subjective feeling pleasantness. From the score plot it can be seen that if the has a low reverberation feeling it also looks to be pleasant.

The three factors fits with the theory of an Evaluation, Potency, Activity (EPA) structure [Summers, 1970]. The evaluation dimension fits with spaciousness, potency with pleasantness and activity with reverberation.

As the factors for the sound segment has been determined the same procedure will now applied to the comfort segment. The correlation matrix can be seen on table M.4. All variables correlate at least 0.3 with one other parameter meaning no variable will be discarded.

	Sleepy/Awake	Enclosed/Open	Uncomfortable/Comfortable	Disinterested/Commited	Small/Large	Sad/Happy	Dull/Energetic	Pessimistic/Optimistic	Inattentive/Attentive	Uneasy/Calm	Dispirited/Lively	Stressed/Relaxed
Sleepy/Awake	**1.00**	0.52	0.25	0.32	0.24	0.29	0.65	0.49	0.40	-0.16	0.30	-0.22
Enclosed/Open	0.52	**1.00**	0.18	0.15	0.31	0.38	0.36	0.40	0.38	0.10	0.04	0.10
Uncomfortable/Comfortable	0.25	0.18	**1.00**	-0.00	0.22	0.48	0.17	0.35	0.28	0.37	0.17	0.44
Disinterested/Commited	0.32	0.15	-0.00	**1.00**	0.14	0.25	0.56	0.42	0.58	0.01	0.44	0.09
Small/Large	0.24	0.31	0.22	0.14	**1.00**	0.12	0.22	0.38	0.51	0.17	0.34	0.16
Sad/Happy	0.29	0.38	0.48	0.25	0.12	**1.00**	0.28	0.66	0.36	0.59	0.27	0.57
Dull/Energetic	0.65	0.36	0.17	0.56	0.22	0.28	**1.00**	0.55	0.56	-0.17	0.56	-0.05
Pessimistic/Optimistic	0.49	0.40	0.35	0.42	0.38	0.66	0.55	**1.00**	0.65	0.48	0.42	0.46
Inattentive/Attentive	0.40	0.38	0.28	0.58	0.51	0.36	0.56	0.65	**1.00**	0.24	0.49	0.21
Uneasy/Calm	-0.16	0.10	0.37	0.01	0.17	0.59	-0.17	0.48	0.24	**1.00**	0.16	0.59
Dispirited/Lively	0.30	0.04	0.17	0.44	0.34	0.27	0.56	0.42	0.49	0.16	**1.00**	0.14
Stressed/Relaxed	-0.22	0.10	0.44	0.09	0.16	0.57	-0.05	0.46	0.21	0.59	0.14	**1.00**

Table M.4: Correlation Matrix for the comfort category.

From the scree plot seen on figure M.29 three factors will be included in the factor analysis. The reason is both that 3 eigenvalues are above 1 and that the knee point looks to be at three factors.

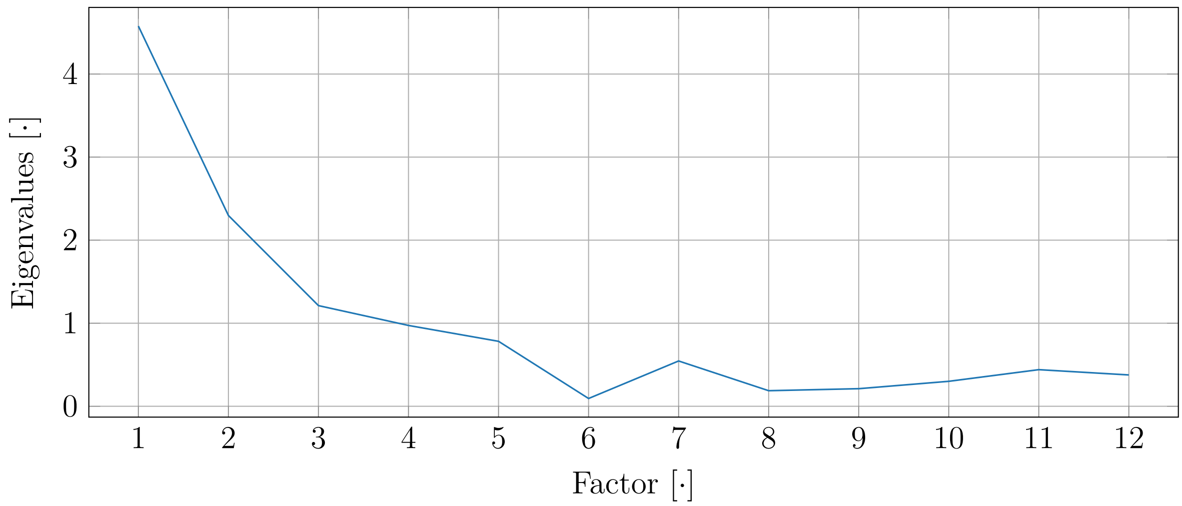


Figure M.29: Scree plot for the comfort segment.

The same methods used for the sound segment have been applied to the comfort segment. The loadings can be seen on table M.5. One outlier was removed.

	Factor 1 (38.43%)	Factor 2 (22.16%)	Factor 3 (8.60%)
Sleepy/Awake	**1.31**	0.45	0.24
Enclosed/Open	**0.69**	-0.06	0.24
Uncomfortable/Comfortable	0.35	-0.39	0.27
Disinterested/Commited	**0.51**	-0.13	**-0.54**
Small/Large	0.34	-0.20	-0.13
Sad/Happy	0.45	**-0.57**	0.22
Dull/Energetic	**0.91**	0.09	-0.45
Pessimistic/Optimistic	**0.65**	-0.48	-0.04
Inattentive/Attentive	**0.59**	-0.31	-0.36
Uneasy/Calm	0.06	**-0.82**	0.24
Dispirited/Lively	0.35	-0.15	-0.31
Stressed/Relaxed	0.04	**-0.95**	0.09

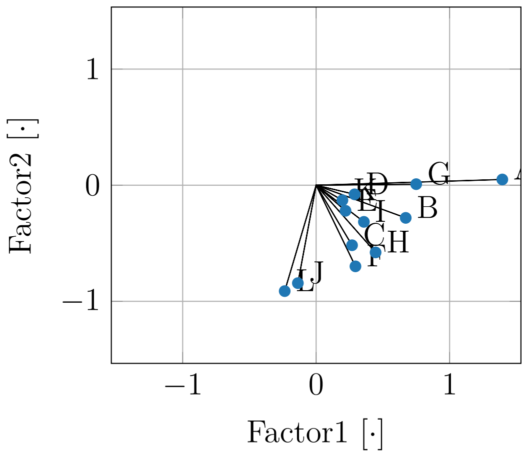
(a) Loading matrix

	Factor 1 (30.74%)	Factor 2 (24.06%)	Factor 3 (14.39%)
Sleepy/Awake	**1.40**	0.05	-0.11
Enclosed/Open	**0.67**	-0.28	-0.02
Uncomfortable/Comfortable	0.27	**-0.52**	0.05
Disinterested/Commited	0.29	-0.08	**-0.69**
Small/Large	0.22	-0.22	-0.27
Sad/Happy	0.29	**-0.70**	-0.07
Dull/Energetic	**0.75**	0.01	**-0.69**
Pessimistic/Optimistic	0.45	**-0.58**	-0.35
Inattentive/Attentive	0.36	-0.32	**-0.59**
Uneasy/Calm	-0.14	**-0.84**	0.02
Dispirited/Lively	0.20	-0.13	-0.43
Stressed/Relaxed	-0.24	**-0.91**	-0.13

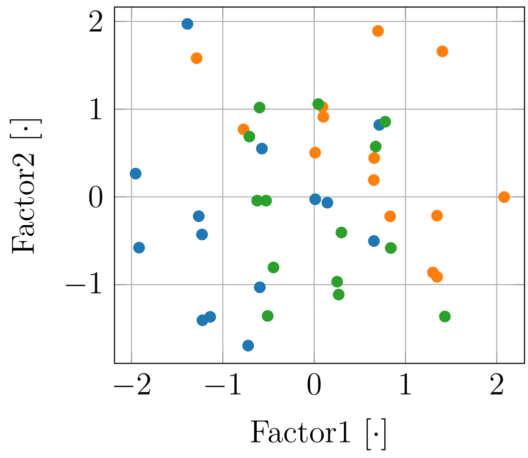
(b) Rotated Loading matrix

Table M.5: Loading matrix from the factor analysis result on comfort.

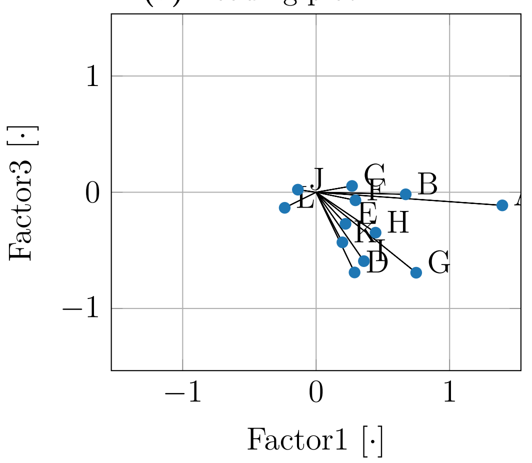
The loadings and score plot can be seen on figure M.30. The interpretation of each factor can be seen below.



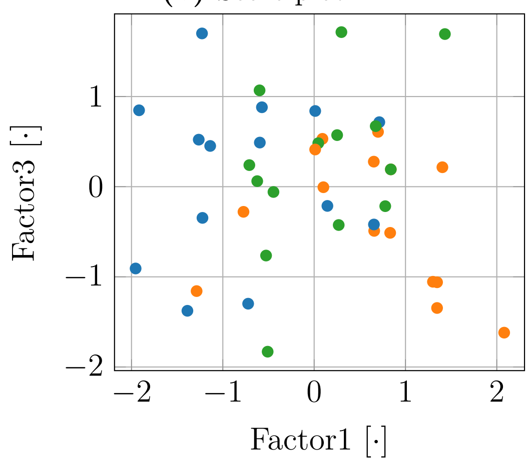
(a) Loading plot.



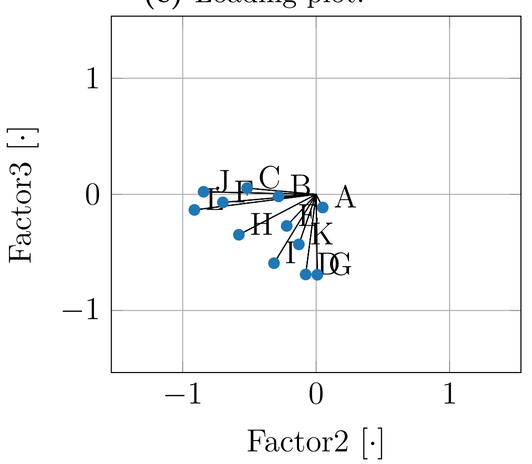
(b) Score plot.



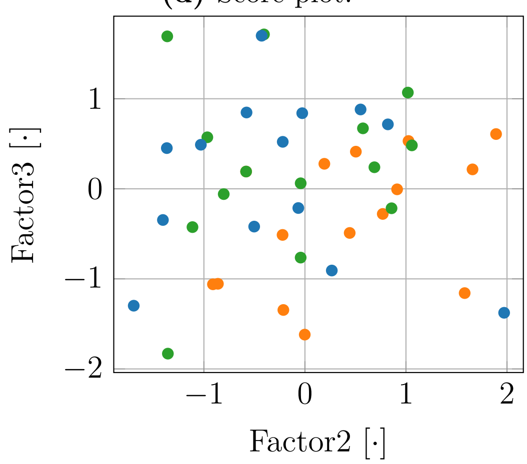
(c) Loading plot.



(d) Score plot.



(e) Loading plot.



(f) Score plot.

Figure M.30: Loading and score plot for the comfort segment. The scales are denoted Sleepy/Awake (A), Enclosed/Open (B), Uncomfortable/Comfortable (C), Disinterested/Committed (D), Small/Large (E), Sad/Happy (F), Dull/Energetic (G), Pessimistic/Optimistic (H), Inattentive/Attentive (I), Uneasy/-Calm (J), Dispirited/Lively (K) and Stressed/Relaxed (L). The rooms are bedroom (●), kitchen (●), living room (●).

Factor 1 is based on sleepy/awake, dull/energetic and enclosed/open with a heavy loading on sleepy/awake. The factor is interpreted as activity which is linked more to the use of the room than an acoustic trait as most bedrooms show a very clear sign of sleepy and kitchens show more signs of awake.

Factor 2 is based on stressed/relaxed, uneasy/calm, sad/happy, pessimistic/optimistic and uncomfortable/comfortable. The variables pessimistic/optimistic and uncomfortable/comfortable could be discarded because of a weak loading. The factor is interpreted as how content a respondent is. From the score plot there is again a clear distinction between the three rooms.

Factor 3 is based on disinterested/committed, dull/energetic and inattentive/attentive. The factor is interpreted as interest. From the score plot it is more difficult than the other two factors to distinguish the room from each other.

The EPA structure could maybe also be applied to the three comfort factors it is however more difficult than the sound segment. Factor 3 does not have very high loadings and one loading is strongly correlated to factor 1. Therefore it could be considered to discard factor 3 as they also from an interpretation view seems very alike.

M.7 | Correlating Subjective and Objective Parameters

All the different subjective and objective parameters have now been reduced to the factors:

- Objective factors: reverberation, absorption
- Sound factors: subjective reverb, spaciousness, pleasantness
- Comfort factors: activity, content, interest

These will now be correlated to explore which factors influences satisfaction and if e.g. the subjective reverberation is dependent on reverberation or absorption. The scores from each factor analysis is used again in a new factor analysis. This is inspired by Multiple Factor Analysis (MFA) [Hervé et al.]. The first factors and ratings correlated are objective factors, sound factors and satisfaction ratings. The correlation matrix can be seen below.

	Reverberation	Absorption	Subjective Reverb	Spaciousness	Pleasantness	Satisfaction
Reverberation	**1.00**	0.02	-0.31	-0.22	0.17	-0.06
Absorption	0.02	**1.00**	-0.08	0.01	-0.23	-0.30
Subjective Reverb	-0.31	-0.08	**1.00**	-0.02	0.11	0.21
Spaciousness	-0.22	0.01	-0.02	**1.00**	0.04	0.18
Pleasantness	0.17	-0.23	0.11	0.04	**1.00**	0.28
Satisfaction	-0.06	-0.30	0.21	0.18	0.28	**1.00**

Table M.6: Correlation Matrix for the objective parameters, the sound segment and satisfaction.

By visual inspection it seen that the correlation between the parameters is not very high. As mentioned earlier, it is desirable to have a correlation >0.3, discarding any parameter below. The spaciousness parameter fails to achieve this requirement, but since the relative correlation between each parameter is low, it is accepted. A low correlation will most likely result in difficulties describing the variance. From the scree plot seen on figure M.31 three factors should be used.

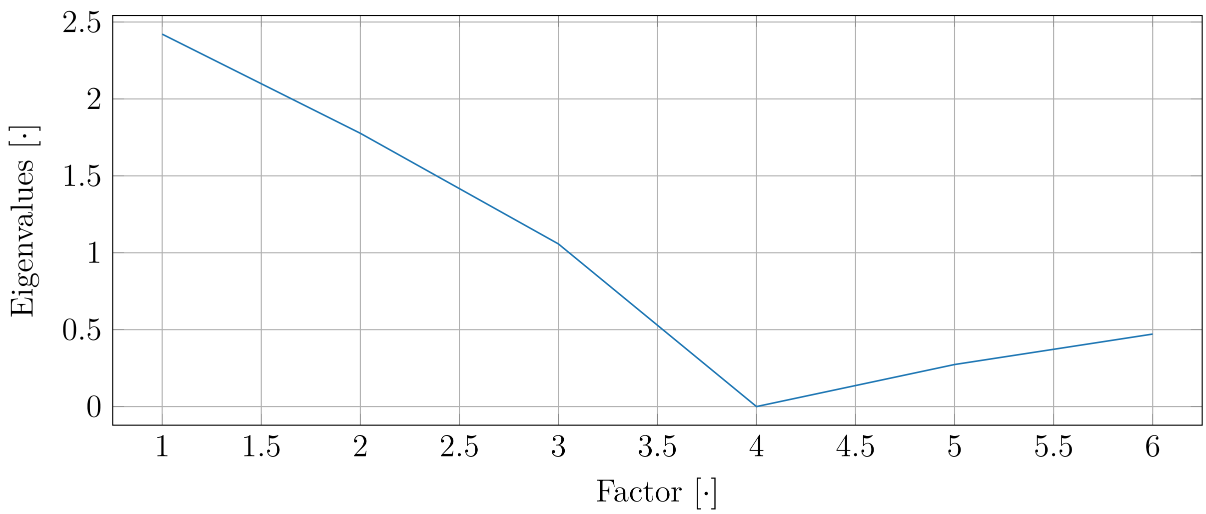


Figure M.31: Scree plot.

The loadings can be seen on table M.7.

	Factor 1 (16.87%)	Factor 2 (13.73%)	Factor 3 (6.86%)
Reverberation	**0.59**	0.43	-0.01
Absorption	0.23	-0.36	0.04
Subjective Reverb	**-0.53**	-0.00	-0.37
Spaciousness	-0.32	-0.05	**0.51**
Pleasantness	-0.14	**0.54**	-0.01
Satisfaction	-0.45	0.46	0.09

(a) Loading matrix

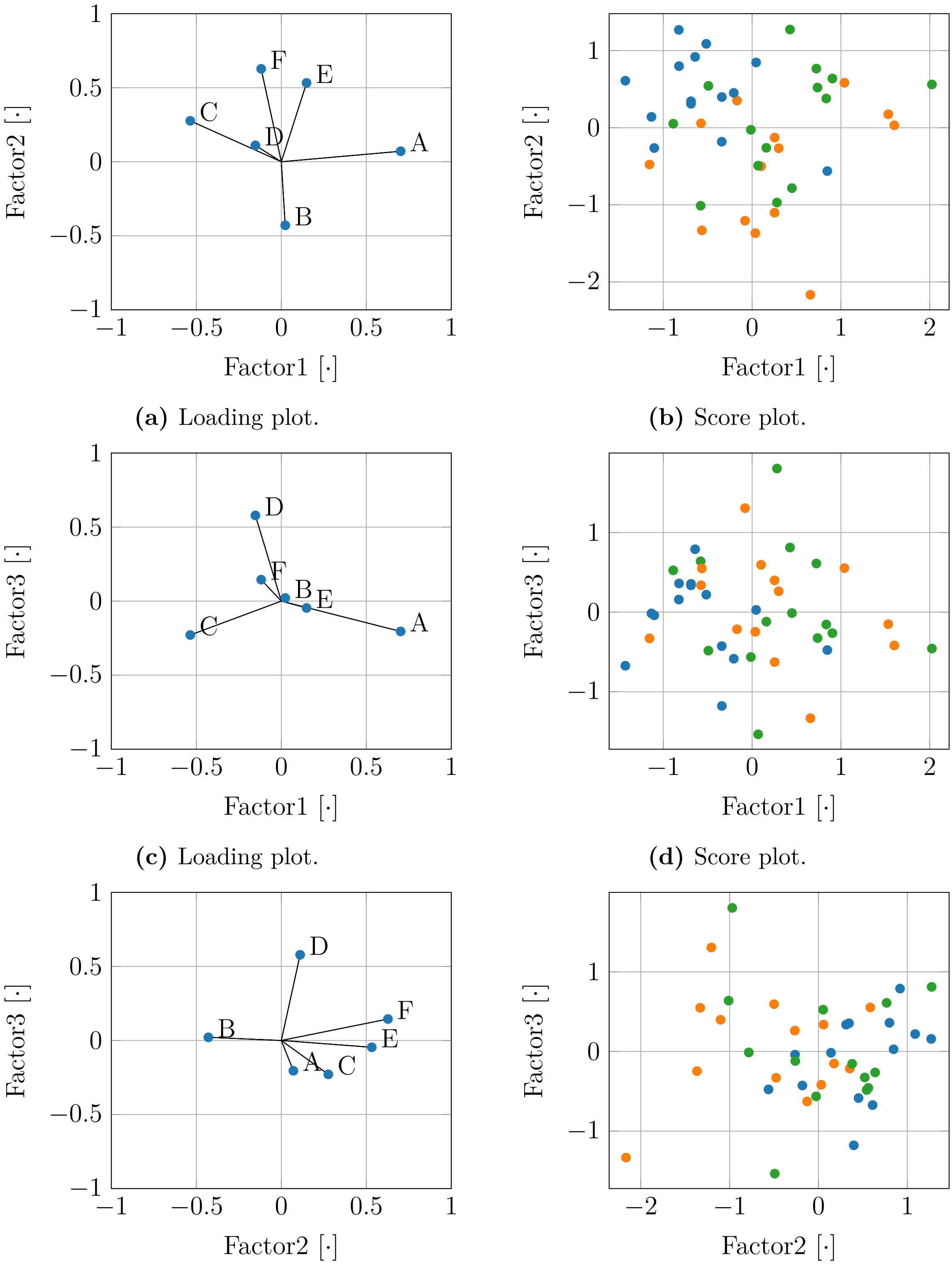
	Factor 1 (14.00%)	Factor 2 (15.91%)	Factor 3 (7.55%)
Reverberation	**0.70**	0.07	-0.20
Absorption	0.02	-0.43	0.02
Subjective Reverb	**-0.54**	0.28	-0.23
Spaciousness	-0.15	0.11	**0.58**
Pleasantness	0.15	**0.53**	-0.05
Satisfaction	-0.12	**0.63**	0.14

(b) Rotated Loading matrix

Table M.7: Loading matrix.

The loadings and score plot can be seen on figure M.32. The interpretation of the factors can be seen below:

From the loadings a clear correlation can be seen between the parameters. Satisfaction is by far mostly correlated with pleasantness and absorption and not reverberation and spaciousness. The subjective reverb is a correlated with both reverberation and pleasantness. The reason spaciousness is not highly correlated with any of the objective factors is probably because the spacial measures where discarded when choosing which parameters to measure.



(a) Loading plot. **(b)** Score plot.

(c) Loading plot. **(d)** Score plot.

(e) Loading plot. **(f)** Score plot.

Figure M.32: Loading and score plot for the scores of sound segment factors, objective parameter factors and satisfaction. The loadings are denoted reverberation (A), absorption (B), subjective reverb (C), spaciousness (D), pleasantness (E) and satisfaction (F).

The objective factors, the comfort factors and satisfaction are now correlated. The correlation matrix can be seen below.

	Reverberation	Absorption	Activity	Content	Interest	Satisfaction
Reverberation	**1.00**	-0.01	0.27	-0.07	-0.08	-0.05
Absorption	-0.01	**1.00**	0.13	0.35	-0.04	-0.34
Activity	0.27	0.13	**1.00**	-0.00	-0.07	-0.06
Content	-0.07	0.35	-0.00	**1.00**	0.05	-0.20
Interest	-0.08	-0.04	-0.07	0.05	**1.00**	0.23
Satisfaction	-0.05	-0.34	-0.06	-0.20	0.23	**1.00**

Table M.8: Correlation Matrix for the objective parameters, the comfort segment and satisfaction.

From the scree plot seen on figure M.31 two factors will be included in the factor analysis.

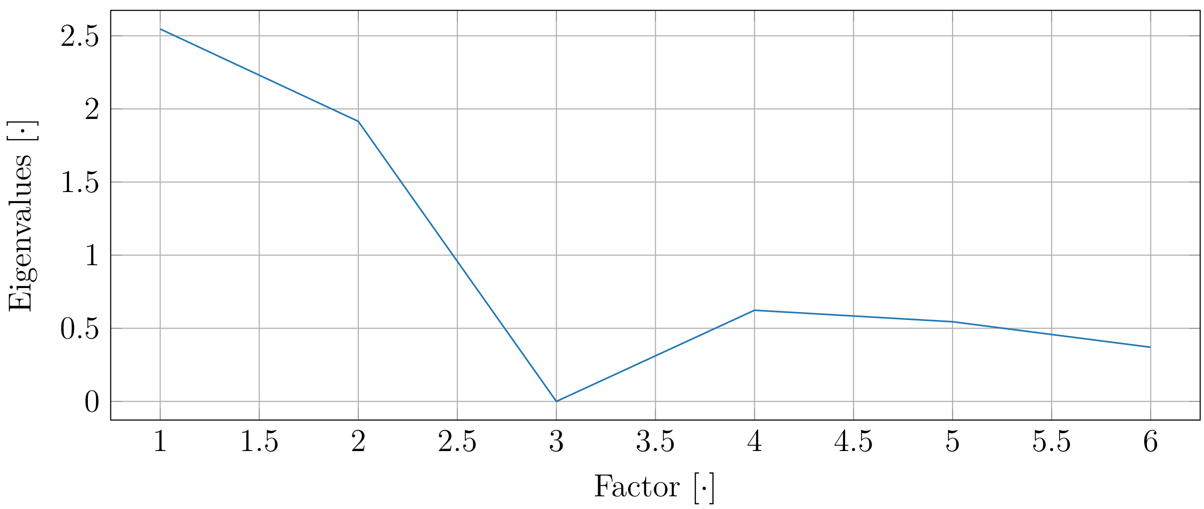


Figure M.33: Scree plot.

The loadings can be seen on table M.9.

	Factor 1 (16.54%)	Factor 2 (9.41%)
Reverberation	0.03	**0.54**
Absorption	**0.69**	-0.05
Activity	0.18	0.45
Content	0.47	-0.20
Interest	-0.13	-0.17
Satisfaction	**-0.50**	-0.06

(a) Loading matrix

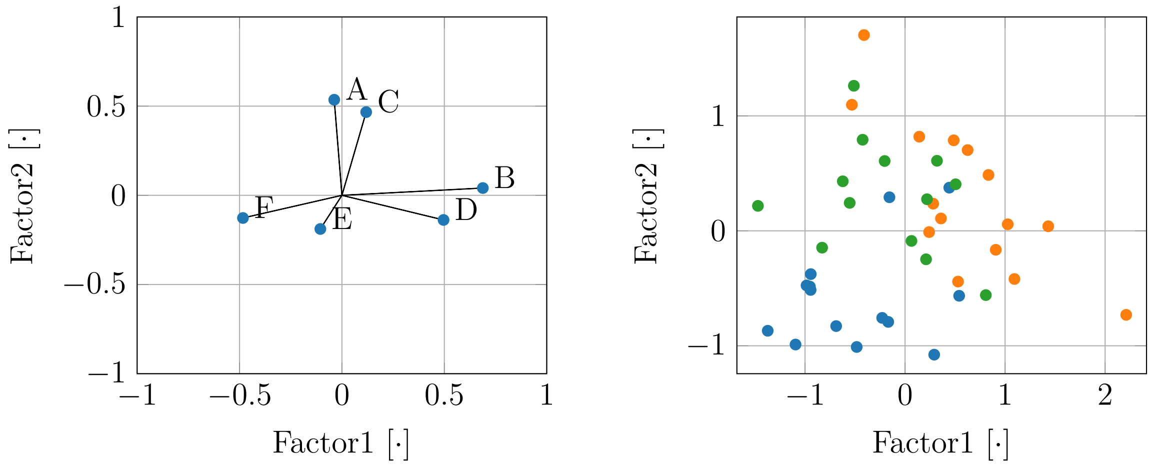
	Factor 1 (16.33%)	Factor 2 (9.62%)
Reverberation	-0.04	**0.54**
Absorption	**0.69**	0.04
Activity	0.12	0.47
Content	**0.50**	-0.14
Interest	-0.11	-0.19
Satisfaction	-0.48	-0.13

(b) Rotated Loading matrix

Table M.9: Loading matrix.

The loadings and score plot can be seen on figure M.34. The interpretation of each factor can be seen below.

As the comfort factors have more to do with the purpose of the room some conclusion can be made from how the factors correlate. It can be seen that rooms which have a high reverberation are primarily used for high activity purposes while rooms with a high absorption are used in rooms where respondents are content. Satisfaction is correlated with both interest and content.



(a) Loading plot.

(b) Score plot.

Figure M.34: Loading and score plot for the scores of comfort segment factors, objective parameter factors and satisfaction. The loadings are denoted reverberation (A), absorption (B), activity(C), content (D), interest (E) and satisfaction (F).

N | Impulse Response of Loudspeakers

N.1 | Purpose

The purpose of these measurements are to determine the frequency response of the two loudspeakers used during the measurement campaign. The impulse responses are needed for determining the strength parameter.

N.2 | Method

This section describes the different methods used throughout the set up and measurements.

N.2.1 Calibration

This section describes how the calibration procedure was performed. All procedures are handled by the BAMPI interface, with the user only specifying either record time or frequency of interest.

Inputs

The inputs was not calibrated during these measurements, but loaded from a workspace. Detailed calibration information is noted in section N.3.2.

Outputs

The outputs was not calibrated during these measurements, but loaded from a workspace. Detailed calibration information is noted in section N.3.2.

Microphones

The microphones have been calibrated using the following procedure:

1. All amplification stages in the gain chain is determined prior.
2. Apply a known sound pressure, to the microphone.
3. Record the sound pressure for a user defined amount of time.
4. Fourier transform the signal.
5. Normalize the signal by its length and account for single sided spectrum[Yu, 2014].
6. Determine the quotient between the Fourier transformed signal and the known sound pressure level.
7. Multiply value to convert between Pascal and voltage on the input.

N.3 | Equipment and Settings

This section contains all equipment used for performing the measurements. Table N.1 lists the equipment used.

N.3.1 Equipment List

Item no.	Description/Name	Serial no.	Internal reference no.
1	Computer with Windows 10 and version 1.0.0 of BAMPI.	NaN	NaN
2	Fireface UFX II	23788354	AAU 108228
3	B&O ICEPOWER Custom Amplifier	00005	NaN
4	Bruel & Kjaer Omni Power Type 4292-L	05005	NaN
5	GRAS 26CA	277294	AAU 88855
6	Bruel & Kjaer UA0196	NaN	NaN
7	GRAS 40AZ	100231	AAU 75522
8	Bruel & Kjær OmniPower 4296	2251009	AAU 33950

Table N.1: List of equipment.

N.3.2 Settings

This section contains all settings chosen for the performed measurements.

Bold dates	describes denotes a value calibrated during the measurement.
Regular date	denotes a value loaded from a workspace file with defined calibration values.
Italic Dates	describes a value that has been manually altered by a user.

Sound card and Computer

The sound card is configured with the following settings:

Samplerate	48000
Buffer size	1024
Driver	ASIO

The measurements were performed on a computer with Windows 10 and version 1.0.0 of BAMPI. By selecting ASIO driver it is ensured that any additional audio driver installed does not interfere with recordings or playback [Steinberg, 2017]. The Buffer size is set to 1024.

Input and Output Sensitivity

Input no.	Gain $\frac{Number}{volt}$ [dBFS]	Date of Calibration
1	-19.87	4/5/2018
9	-19.12	4/5/2018

(a) Input sensitivity.

Output no.	Gain $\frac{volt}{number}$ [dBFS]	Date of Calibration
1	7.72	4/5/2018

(b) Output sensitivity.

Table N.2: Input and output gains with the respective sensitivity and date of calibration.

Microphones

Item no.	Name	Channel	Sensitivity $[\frac{mV}{Pa}]$	Date of calibration
7	GRAS 40AZ	9	46.30	**29/5/2018**

Table N.3: All microphones used with their respective sensitivity, channel location and calibration date.

Amplifiers

Item no.	Name	Channel	Gain $[dBV]$
5	GRAS 26CA	9	-0.30
6	Bruel & Kjaer UA0196	9	1.00
3	B&O ICEPOWER Custom	1	30.00

Table N.4: All amplifiers for both input and output used along with their respective gain and channel location

N.4 | Diagrams and Pictures

N.4.1 Peripheral Connections

This section describes the different connections to the sound card and all the peripherals used. It should be noted that the wirings on figure N.1 is not noted with the specific type of cable used.

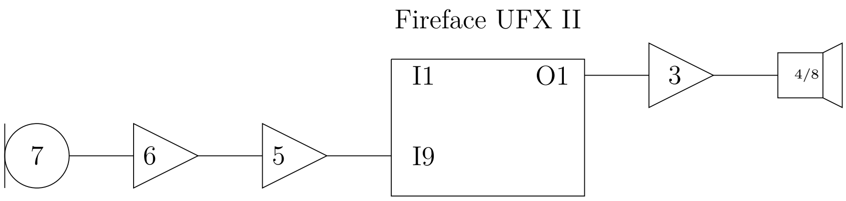


Figure N.1: Schematic of the soundcard and all connected periperals.

Output channel 1 is connected to input channel 1 and is used as reference signal

N.4.2 Microphone and loudspeaker positioning

During the experiment, the measurement setup shown on figure N.2 was used. The three microphone positions was placed at 0.8, 1.8 and 3.8 meters away from the source. The 20 centimeters account for the size of the speaker being between 30 - 40 centimeters in diameter and assumes the acoustic center to be inside in the actual speaker. Figure N.2 shows an overview of the anechoic chamber at Aalborg university. The figures display grills used for placement of loudspeaker and microphone. The orientation of the loudspeaker is done such a driver is pointing towards the loudspeaker attenuating the artifact coming from the edges of the loudspeaker. It should be noted that the placement is not ideal, but is chosen based on availability in the room, as seen in the following pictures.

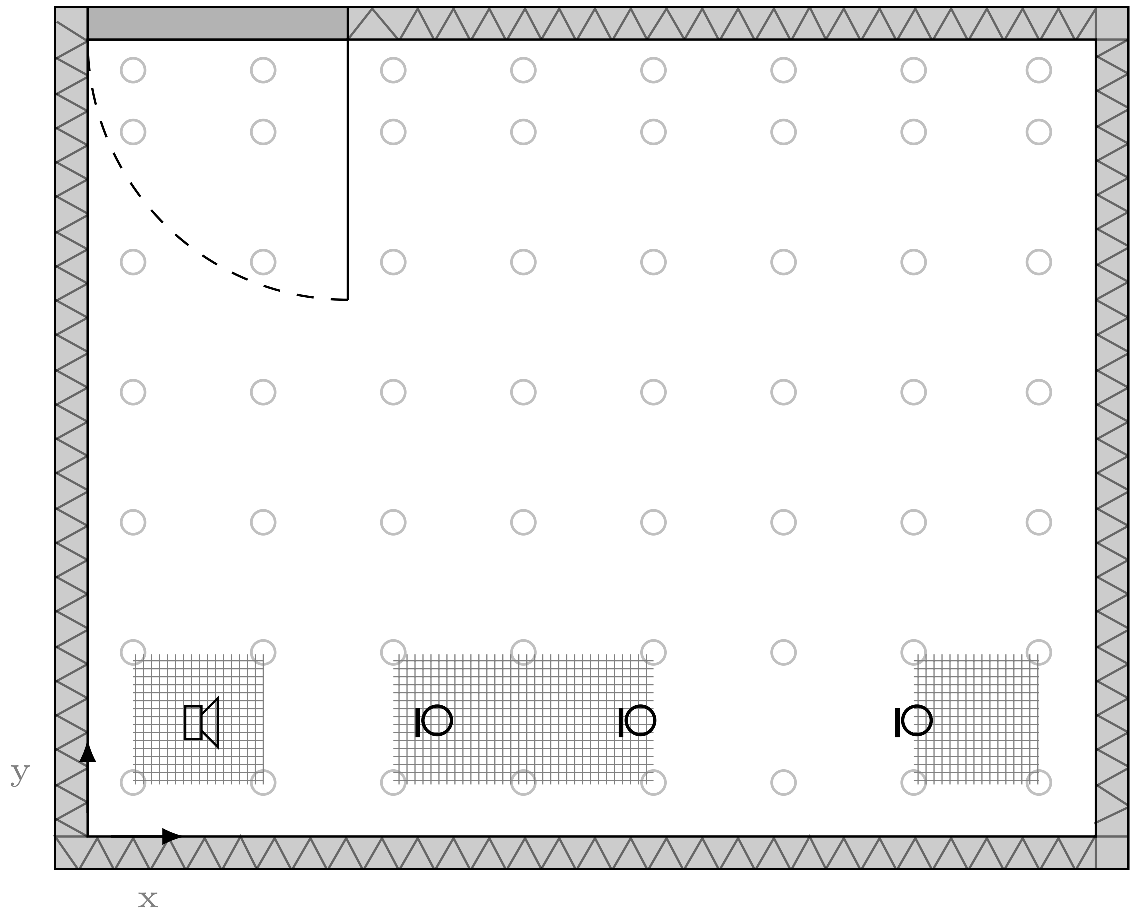


Figure N.2: Graphical representation of microphone and source positions in the anechoic room at Aalborg University. The gray circles displays places where rods could be positioned for placing the metal grids on which the loudspeaker and microphones are placed on.

N.5 | Pictures

(a) OmniPower 4292-L (Loudspeaker 1)

(b) OmniPower 4296 (Loudspeaker 2)

Figure N.3: The two loudspeakers undergoing measurement

Figure N.4: The microphone.

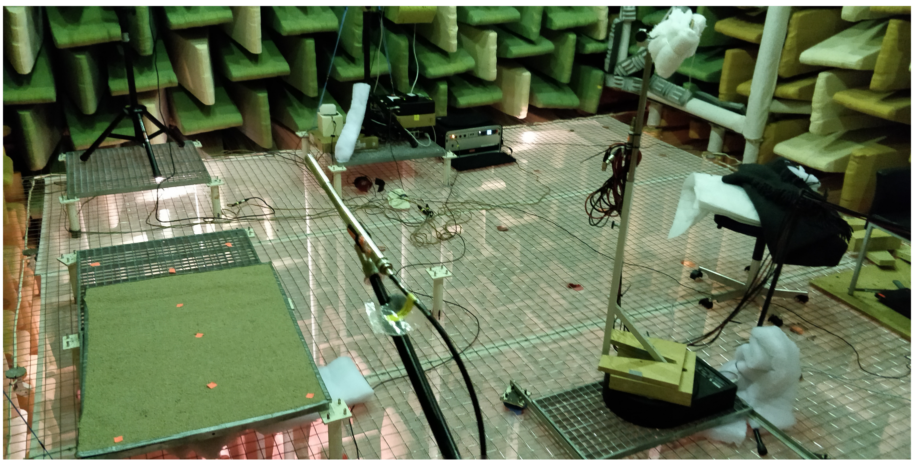


Figure N.5: The room picture 1.

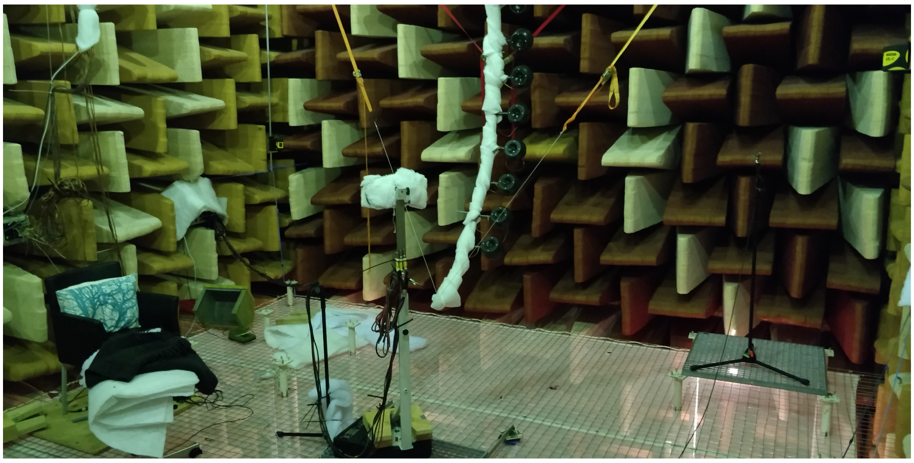


Figure N.6: The room picture 2.

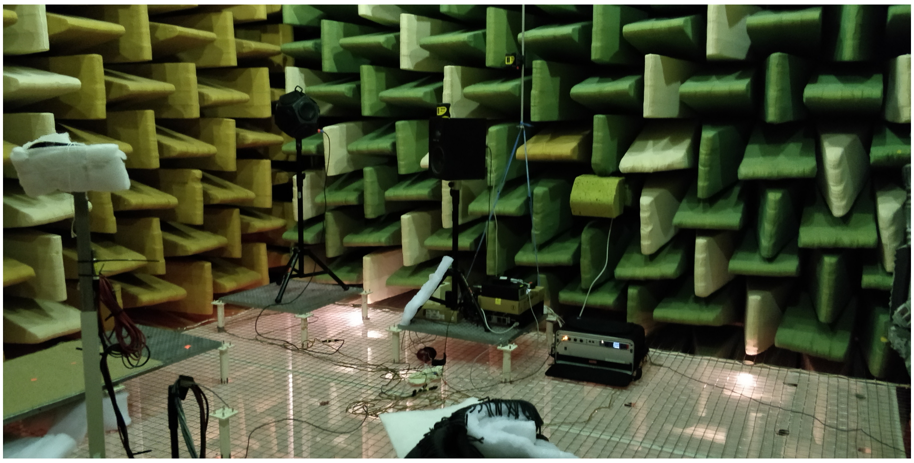


Figure N.7: The room picture 3.

N.6 | Procedural Check List

1. Place loudspeaker 1
2. Place microphone 1 m away from the loudspeaker
3. Perform measurement
4. Validate measurement
5. Repeat step 2,3,4 for 2 m and 4 m
6. Repeat all steps for loudspeaker 2

N.7 | Measurements

What follows are all single measurements showing the sound pressure level at 1 meter distance along with the calculated impulse response for all three distances in both time and frequency. All measurement were done with an ambient temperature of 22 degrees Celsius and 30 % relative humidity. Table N.5 denotes the gains settings applied by the user during the measurements.

Output Channel	Gain Setting [dB]
1	-6.0

Table N.5: Gain values specified by user.

N.7.1 Measurement 1

Loudspeaker 1 measured at a distance of 1 meter.

Stimuli

During measurement 1, the following stimuli was used on their respective channels. All sweeps are synthesized in frequency [Müller and Massarani, 2001]

- Channel 1: Settings for Stimuli: Sweep - Type: Log - Time: 5.0 - Frequency Range: 50.0-12000.0, Degree of Linearty: 99.77 Zero padding before 0.0 [s] and after 0.5 [s]

Filter Settings (Inputs)

- Channel 9: Filter Settings: LP: Passband 0.1 [dB] @ 9878.0 [Hz], Stopband 20.0 [dB] @ 16000.0 [Hz], HP Passband 0.1 [dB] @ 40.0 [Hz], Stopband 20.0 [dB] @ 25.0 [Hz]

Analysis of measurement 1

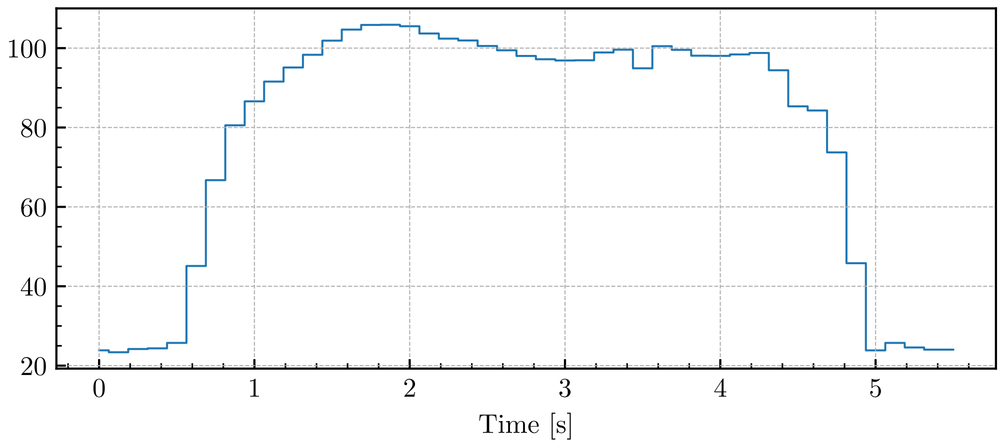


Figure N.8: Linear time average (tau = 0.125 [s]) of input CH9 (●) [SPL].

The SPL at 1 m distance is approximately 100 dB SPL.

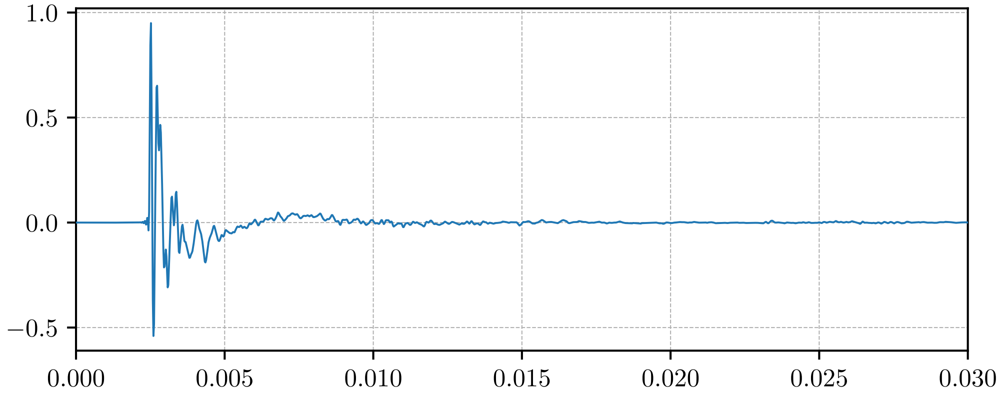


Figure N.9: Impulse response of input CH9 (●) [Pascal/Volt].

The calculated impulse response.

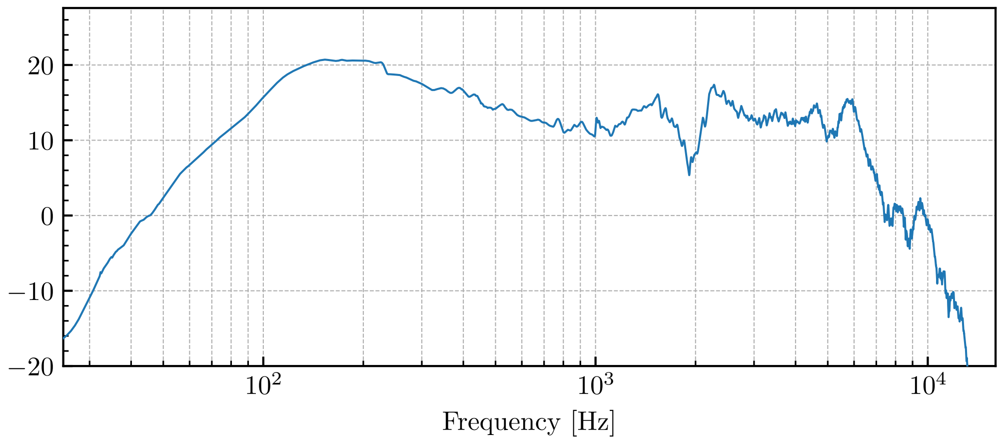


Figure N.10: Single sided magnitude response (N = 264000 [.]) of input impulse response CH9 (●) [Pascal/Volt].

The magnitude response of the impulse response. Notice the dip at 2 kHz. The dip is an artifact of the edges on the loudspeaker. The is suppress as much as possible by pointing the loudspeaker directly at the microphone.

N.7.2 Measurement 2

Loudspeaker 1 measured at a distance of 2 meter.

Stimuli

During measurement 2, the following stimuli was used on their respective channels. All sweeps are synthesized in frequency [Müller and Massarani, 2001]

- Channel 1: Settings for Stimuli: Sweep - Type: Log - Time: 5.0 - Frequency Range: 50.0-12000.0, Degree of Linearty: 99.77 Zero padding before 0.0 [s] and after 0.5 [s]

Filter Settings (Inputs)

- Channel 9: Filter Settings: LP: Passband 0.1 [dB] @ 9878.0 [Hz], Stopband 20.0 [dB] @ 16000.0 [Hz], HP Passband 0.1 [dB] @ 40.0 [Hz], Stopband 20.0 [dB] @ 25.0 [Hz]

Analysis of measurement 2

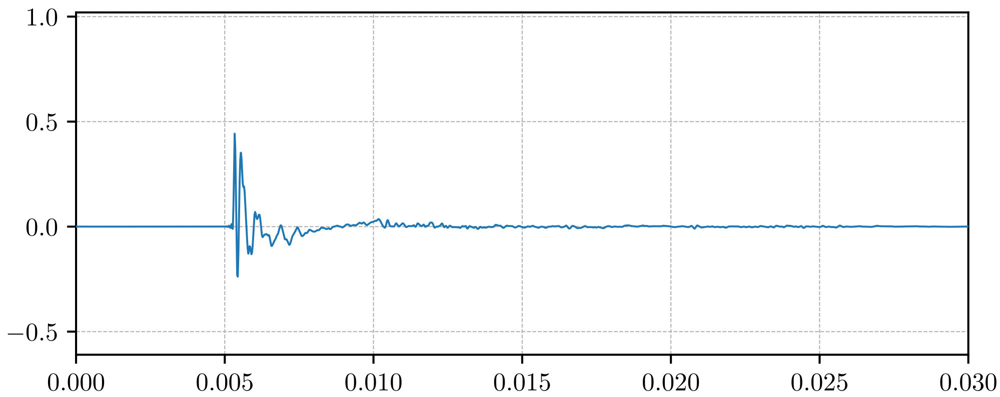


Figure N.11: Impulse response of input CH9 (●) [Pascal/Volt].

The impulse response. A decrease is clearly shown alongside a doubling in delay.

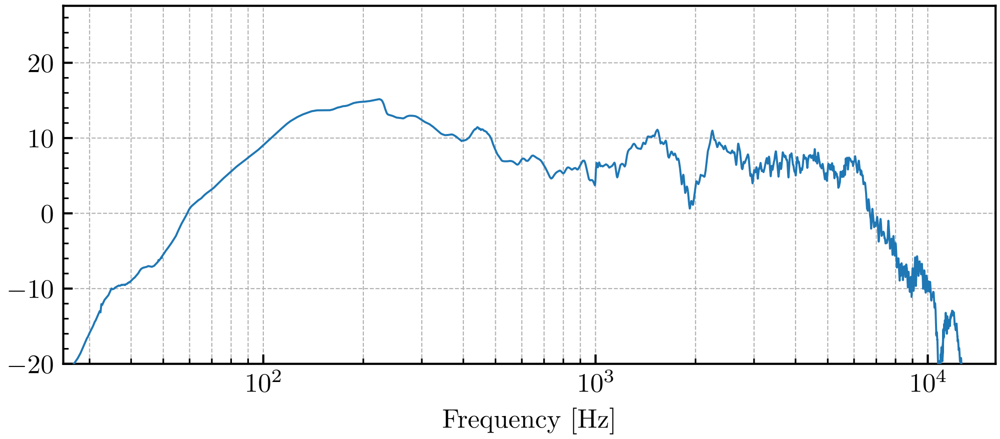


Figure N.12: Single sided magnitude response (N = 264000 [.]) of input impulse response CH9 (●) [Pascal/Volt].

The magnitude response of the impulse response from 2 meters distance. A 6 db attenuation from measurement 1 is seen.

N.7.3 Measurement 3

Loudspeaker 1 measured at a distance of 4 meter.

Stimuli

During measurement 3, the following stimuli was used on their respective channels. All sweeps are synthesized in frequency [Müller and Massarani, 2001]

- Channel 1: Settings for Stimuli: Sweep - Type: Log - Time: 5.0 - Frequency Range: 50.0-12000.0, Degree of Linearty: 99.77 Zero padding before 0.0 [s] and after 0.5 [s]

Filter Settings (Inputs)

- Channel 9: Filter Settings: LP: Passband 0.1 [dB] @ 9878.0 [Hz], Stopband 20.0 [dB] @ 16000.0 [Hz], HP Passband 0.1 [dB] @ 40.0 [Hz], Stopband 20.0 [dB] @ 25.0 [Hz]

Analysis of measurement 3

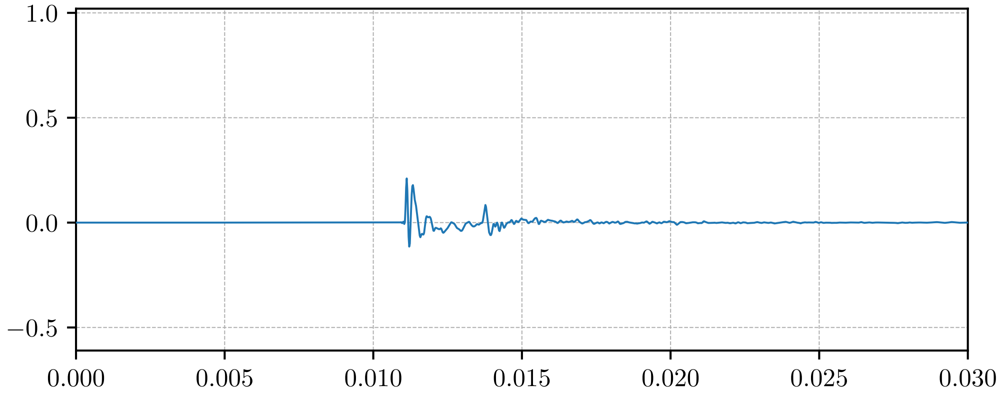


Figure N.13: Impulse response of input CH9 (●) [Pascal/Volt].

The impulse response calculated at 4 meters distance. A doubling in delay is seen with a further decrease in amplitude. A second impulse is seen shortly after the main impulse. The second impulse is a reflection from the surrounding setups.

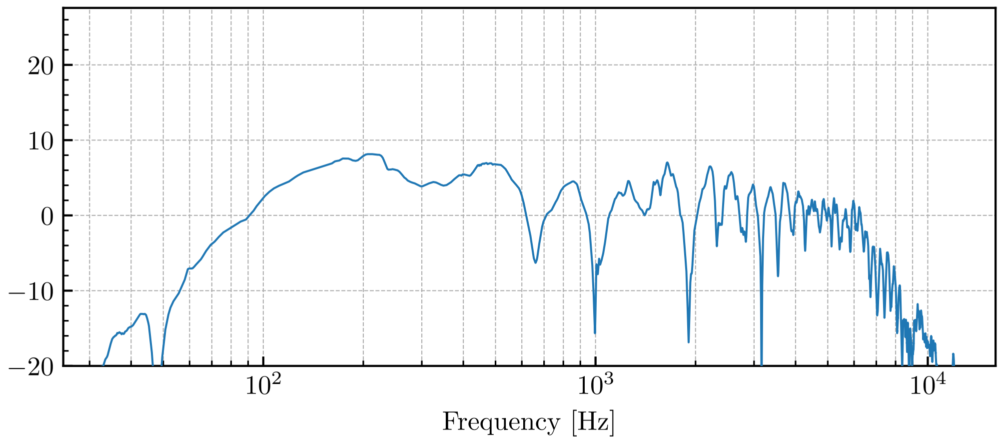


Figure N.14: Single sided magnitude response (N = 264000 [.]) of input impulse response CH9 (●) [Pascal/Volt].

The frequency response at 4 meter now show serve artifacts like comb filter effects and reflections from surroundings now influence the impulse. With this setup it is not possible to measure properly at 4 meters distance.

N.7.4 Measurement 4

Loudspeaker 2 measured at a distance of 1 meter.

Stimuli

During measurement 4, the following stimuli was used on their respective channels. All sweeps are synthesized in frequency [Müller and Massarani, 2001]

- Channel 1: Settings for Stimuli: Sweep - Type: Log - Time: 5.0 - Frequency Range: 50.0-12000.0, Degree of Linearty: 99.77 Zero padding before 0.0 [s] and after 0.5 [s]

Filter Settings (Inputs)

- Channel 9: Filter Settings: LP: Passband 0.1 [dB] @ 9878.0 [Hz], Stopband 20.0 [dB] @ 16000.0 [Hz], HP Passband 0.1 [dB] @ 40.0 [Hz], Stopband 20.0 [dB] @ 25.0 [Hz]

Analysis of measurement 4

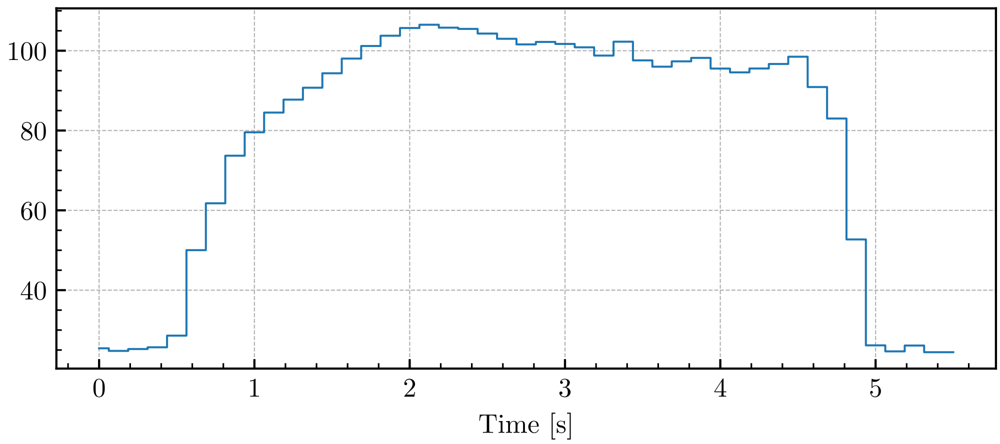


Figure N.15: Linear time average (tau = 0.125 [s]) of input CH9 (●) [SPL].

The SPL at 1 m. The average is approximately 100 dB SPL.

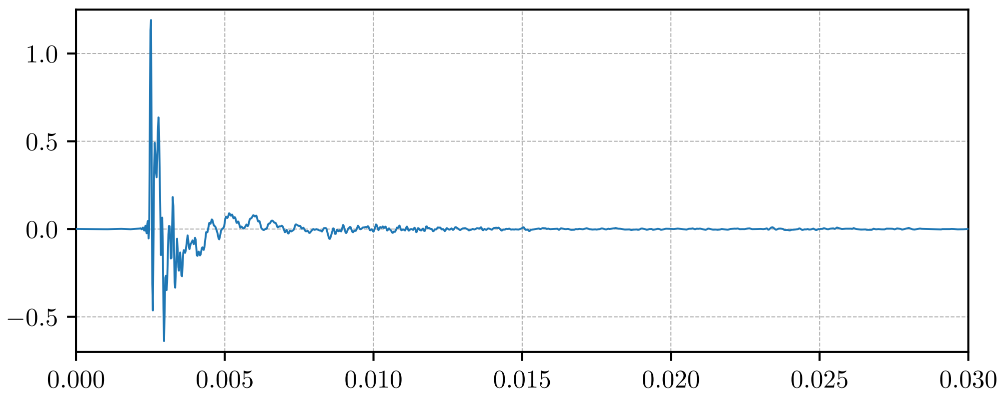


Figure N.16: Impulse response of input CH9 (●) [Pascal/Volt].

The impulse response calculated at 1 meters distance.

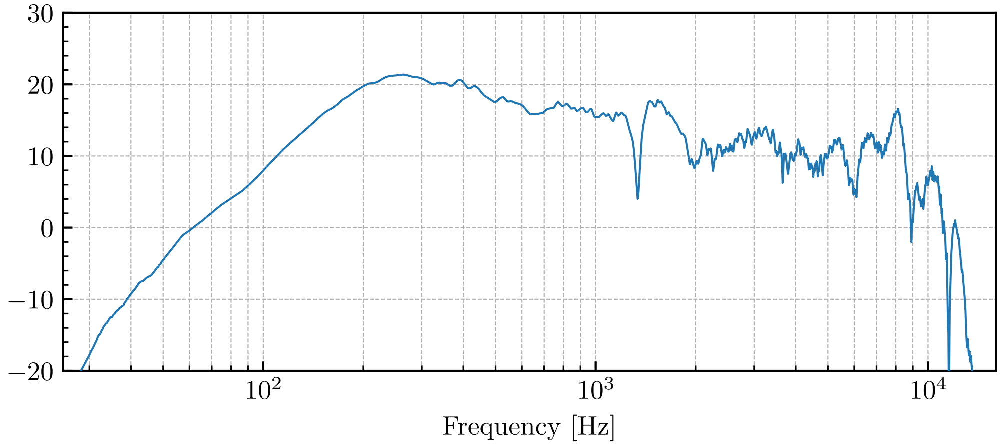


Figure N.17: Single sided magnitude response (N = 264000 [.]) of input impulse response CH9 (●) [Pascal/Volt].

The frequency response at 1 meters distance. The same dip as with the first speaker is also present in this loudspeaker. The dip has shifted approximately 500 Hz downwards in frequency fitting with the different geometry of this speaker.

N.7.5 Measurement 5

Loudspeaker 2 measured at a distance of 2 meter.

Stimuli

During measurement 5, the following stimuli was used on their respective channels. All sweeps are synthesized in frequency [Müller and Massarani, 2001]

- Channel 1: Settings for Stimuli: Sweep - Type: Log - Time: 5.0 - Frequency Range: 50.0-12000.0, Degree of Linearty: 99.77 Zero padding before 0.0 [s] and after 0.5 [s]

Filter Settings (Inputs)

- Channel 9: Filter Settings: LP: Passband 0.1 [dB] @ 9878.0 [Hz], Stopband 20.0 [dB] @ 16000.0 [Hz], HP Passband 0.1 [dB] @ 40.0 [Hz], Stopband 20.0 [dB] @ 25.0 [Hz]

Analysis of measurement 5

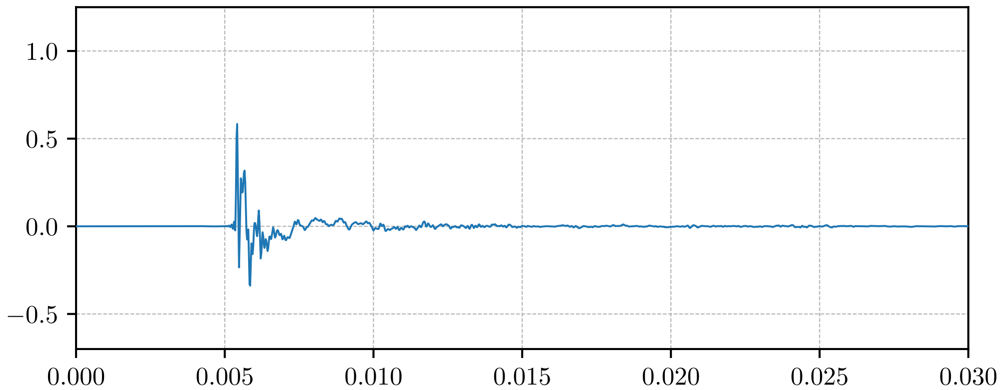


Figure N.18: Impulse response of input CH9 (●) [Pascal/Volt].

The impulse response calculated at 2 meters distance. The impulse show clear doubling in delay and a decrease in amplitude.

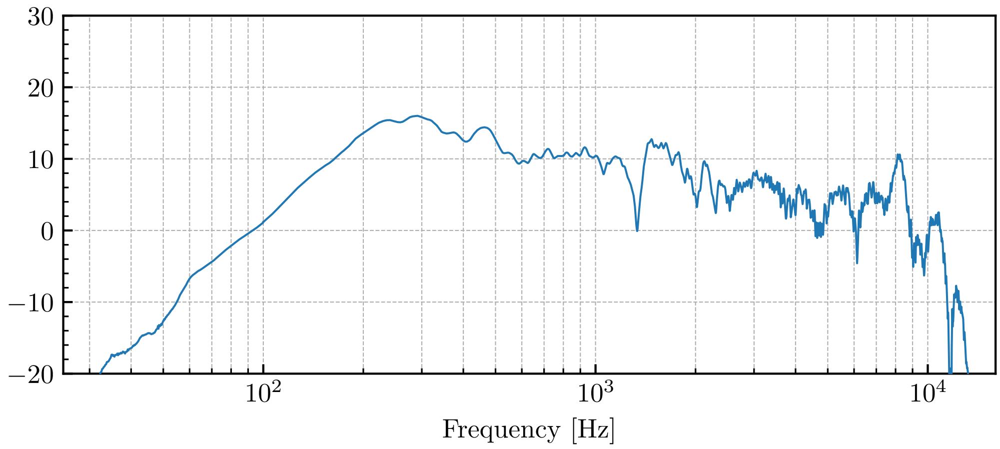


Figure N.19: Single sided magnitude response (N = 264000 [.]) of input impulse response CH9 (●) [Pascal/Volt].

The frequency response of the impulse at 2 meters distance. The frequency response shows a decrease of approximately 6 dB.

N.7.6 Measurement 6

Loudspeaker 2 measured at a distance of 4 meter.

Stimuli

During measurement 6, the following stimuli was used on their respective channels. All sweeps are synthesized in frequency [Müller and Massarani, 2001]

- Channel 1: Settings for Stimuli: Sweep - Type: Log - Time: 5.0 - Frequency Range: 50.0-12000.0, Degree of Linearty: 99.77 Zero padding before 0.0 [s] and after 0.5 [s]

Filter Settings (Inputs)

- Channel 9: Filter Settings: LP: Passband 0.1 [dB] @ 9878.0 [Hz], Stopband 20.0 [dB] @ 16000.0 [Hz], HP Passband 0.1 [dB] @ 40.0 [Hz], Stopband 20.0 [dB] @ 25.0 [Hz]

Analysis of measurement 6

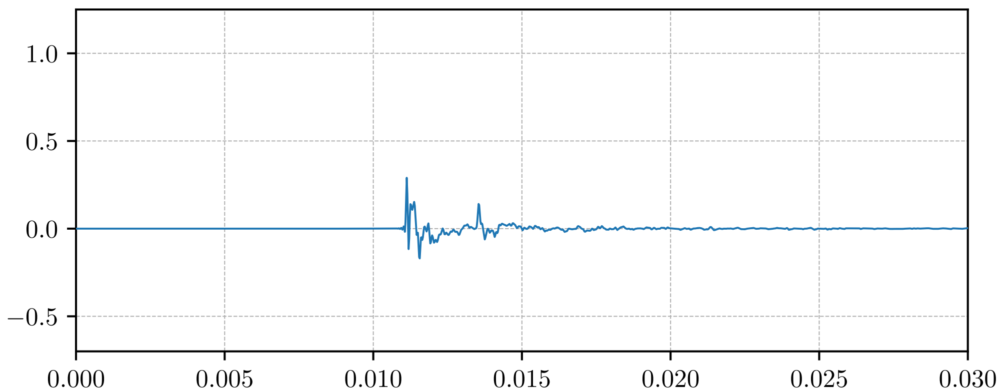


Figure N.20: Impulse response of input CH9 (●) [Pascal/Volt].

The impulse at 4 meters show the expected doubling in delay. The impulse show the same additional impulse as the first speaker. The second impulse occurs from reflections of all the other setups.

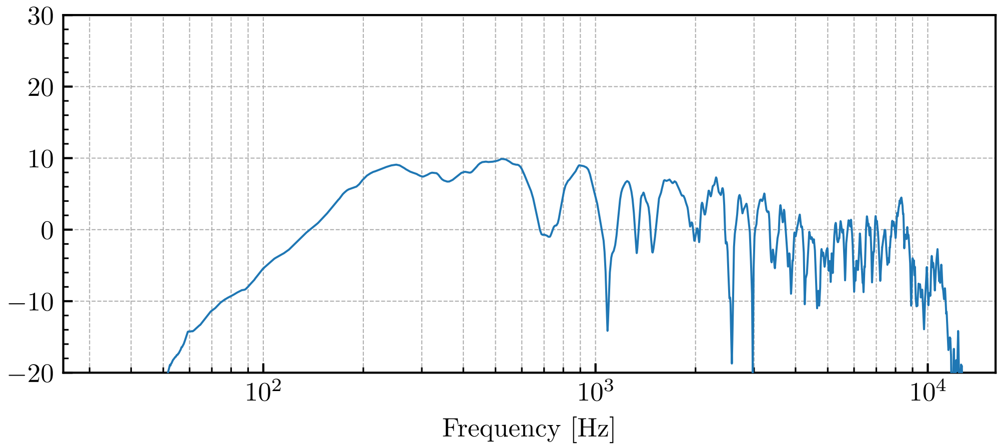


Figure N.21: Single sided magnitude response (N = 264000 [.]) of input impulse response CH9 (●) [Pascal/Volt].

The frequency response at 4 meter now show serve artifacts like comb filter effects and reflections from surroundings now influencing the impulse. With this setup it is not possible to measure properly at 4 meters distance.

N.8 | Results

To verify that the measured response at 1 meter behaves as measured in free field, it is compared with a second measurement from double the distance. If the two impulses behaves as intended, it is to be 6 dB lower. The two impulses are compared in frequency where their magnitude are subtracted from each other bin wise. The results for the two loudspeakers can be seen in figure N.22 and N.23.

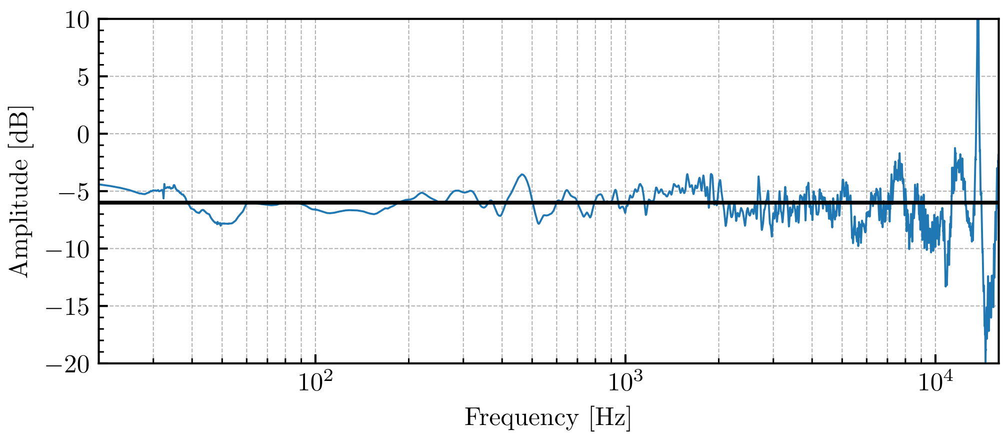


Figure N.22: Comparison between 1 and 2 meter frequency response for 4292-L (●), -6dB line (●)

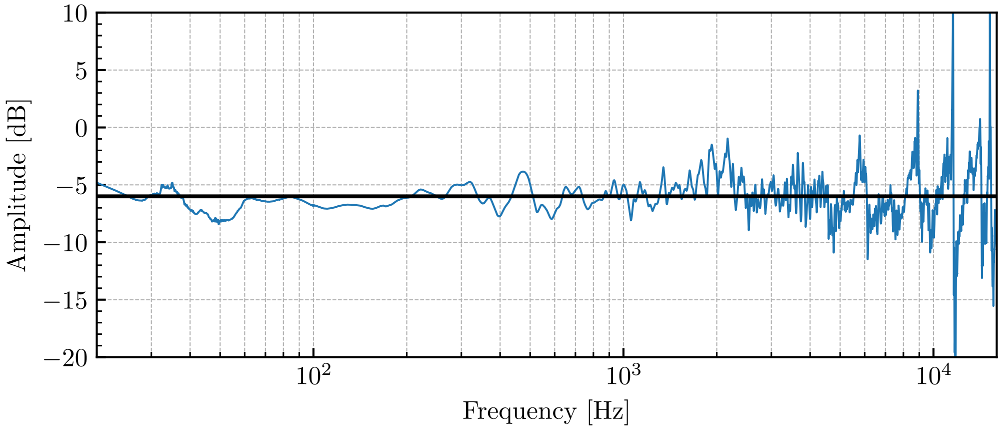


Figure N.23: Comparison between 1 and 2 meter frequency response for 4296 (●), -6dB line (●)

The results show that the majority of the difference is around -6 dB which is as expected for free field conditions. The deviations at higher frequencies are caused by improper placement of the equipment.

N.9 | Tolerances

The following tables shows the tolerances of all noted equipment used for performing measurements. Table N.6 is the input peripherals. Table N.7 is the output peripherals.

Item no.	Name	Tolerance [dB]	Frequency Range [Hz]
5	GRAS 26CA	+0.2/-0.2	2.5 - 20000.0
6	Bruel & Kjaer UA0196	+0.1/-0.1	2.0 - 200000.0
7	GRAS 40AZ	+2.0/-2.0	0.5 - 20000.0

Table N.6: All input peripherals used for performing measurements with their respective tolerances in the stated frequency area.

Item no.	Name	Tolerance [dB]	Frequency Range [Hz]
3	B&O ICEPOWER Custom	+1.0/-1.0	2.0 - 20000.0
4	Bruel & Kjaer Omni Power Type 4292-L	+1.0/-1.0	50.0 - 12000.0

Table N.7: All output peripherals used for performing measurements with their respective tolerances in the stated frequency area.

N.10 | Error

The anechoic room was occupied with several setups at the current time and the setup used in this experiment was placed to close to both walls and equipment. This resulted in both comb filtering effects and additional reflections at the 4 meter distance, drastically deterioration the main impulse. The impulse response at 4 meters are hence not used.

N.11 | Raw Data

All raw data paths mentioned above is enclosed on CD and is structured as shown in figure N.24. All figures not generated within the BAMPI program can be generated in `GetImpulseFigure.py`.

```
Loudspeaker Measurement
├─ Data
│   ├─ Impulses.mat
│   └─ Measurements.mat
├─ Settings
│   ├─ GainSettings.mat
│   ├─ TemplateSettings.ini
│   └─ Workspace.ini
└─ GetImpulseFigure.py
```

Figure N.24: File structure of Loudspeaker measurement.

N.12 | Conclusion

The impulse response of both loudspeakers was obtained.