Henri Kari

Effects of Acoustic Treatment on Sound Environment in Public Buildings

School of Electrical Engineering

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Thesis supervisor:

Prof. Vesa Välimäki

Thesis instructor:

Lic.Sc. (Tech.) Jyrki Kilpikari

Aalto University
School of Electrical
Engineering

AALTO UNIVERSITY
SCHOOL OF ELECTRICAL ENGINEERING

ABSTRACT OF THE
MASTER'S THESIS

Author: Henri Kari

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Supervisor: Prof. Vesa Välimäki

Instructor: Lic.Sc. (Tech.) Jyrki Kilpikari

The effects of acoustical treatment on the sound environment of three different types of public-type spaces were investigated in this thesis. The basic theory of room acoustics and the most common room acoustical parameters are explained in the work. Acoustical conditions and requirements of public spaces are also considered.

The three studied places were a classroom, a healthcare space, and an open plan office. Measurements of common acoustical parameters, such as the reverberation time, the speech transmission index, the rate of spatial decay of sound pressure level per distance doubling, the clarity, and the strength, were performed before and after the acoustical treatment. Various methods and materials, such as ceiling- and wall panels, were used to improve the sound environment of the studied places. The measured places were in normal use after the acoustical renovation.

The performed measurements show that the acoustical treatment clearly enhances the sound environment in each type of space. In the classroom the speech intelligibility has increased and the reverberation time has decreased after the treatment. These changes lead to better learning environment, when students can hear the teacher better and the teacher is able to talk with normal voice. In the healthcare space the reverberation time has decreased offering more pleasant sound environment to the patients. Also, the speech intelligibility has increased, which helps the communication between the patients and the nursing staff. In the open plan office the overall sound pressure level has decreased and the speech intelligibility has decreased between workplaces after the treatment. The obtained sound environment offers more privacy to the employees improving the concentration to the work.

Keywords: acoustics, acoustic measurements, open plan office, classroom, healthcare space

AALTO-YLIOPISTO
SÄHKÖTEKNIIKAN KORKEAKOULU

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Tässä diplomityössä tutkittiin akustoinnin vaikutusta kolmen eri tyyppisen julkisen tilan ääniympäristöön. Huoneakustiikan perusteoria sekä yleisimmät huoneakustiset parametrit käydään läpi. Työssä käsitellään myös julkisten tilojen ääniympäristöjä ja akustisia vaatimuksia kyseisille tiloille.

Tutkitut kohteet olivat luokkahuone, terveydenhoitotila ja avotoimisto. Yleisimmät akustiset parametrit, kuten jälkikaiunta-aika, puheensiirtoindeksi, leviämisvaimennusaste, selkeys ja voimakkuus, mitattiin tutkituissa tiloissa ennen ja jälkeen akustoinnin. Erilaisia tapoja ja materiaaleja, kuten katto- sekä seinälevyjä, käytettiin parantamaan tilojen akustiikkaa. Mitatut tilat olivat normaalissa käytössä akustisen parannuksen jälkeen.

Suoritettujen akustisten mittausten perusteella akustointi parantaa selkeästi jokaisen tilatyypin ääniympäristöä. Luokkahuoneessa puheen erotettavuus on parantunut ja jälkikaiunta-aika on lyhentynyt akustoinnin jälkeen. Näistä muutoksista seuraa parempi oppimisympäristö, kun oppilaat kuulevat opettajan paremmin ja opettaja voi puhua normaalilla äänenvoimakkuudella. Terveydenhoitotilassa jälkikaiunta-aika lyheni tarjoten potilaille miellyttävämmän ääniympäristön. Myös puheen erotettavuus kasvoi, mikä parantaa kommunikaatiota potilaiden ja hoitohenkilökunnan välillä. Avotoimistossa äänipainetaso laski kaikkialla toimistossa ja puheen selkeys laski työpisteiden välillä akustoinnin jälkeen. Saavutettu ääniympäristö antaa työntekijöille enemmän yksityisyyttä lisäten keskittymistä työhön.

Avainsanat: akustiikka, akustiset mittaukset, avotoimisto, luokkahuone, terveydenhoitotila

Preface

This thesis has been written between 1.3.2012 - 30.9.2012 for Ecophon business unit Finland in Pitäjänmäki. Many thanks for Jari Johansson and Jyrki Kilpikari for making all this possible. Measurements were made in the Piikkiö comprehensive school, the Kiinteistö Oy Seinäjoki's Y-building, and the Finnish Real Estate Federation office. I would like to thank all the personnel of before mentioned measurement sites for a fluent collaboration. Also, i would like to thank Finnish Institute of Occupational Health for lending the measurement equipment.

The supervisor of the thesis was Prof. Vesa Välimäki and the instructor of the thesis was Lic.Sc.(Tech.) Jyrki Kilpikari. Both of them offered many advices and encouraged to continue the thesis project. The feedback given on incomplete versions of this work has been invaluable.

I would also like to thank Pauli Pallaskorpi and Arto Rauta for a logistical help and important support, Jouko Hakala for numerous advices and instructions, and all Ecophon personnel for a nice coffee breaks and company.

Great thanks for my parents for all the support during the studentship and for Elina for the encouragement and endless tolerance to my complaining about this work.

Finally I would like to thank all of my friends who, undoubtedly, believed that I would graduate one day.

Pitäjänmäki, 12.9.2012

Henri Kari

Contents

Symbols and acronyms

Symbols

A	Absorption area
c	Speed of sound
C_{50}	Clarity
C_I	Step sound spectral weighting factor
d_{min}	Minimum distance between source and microphone
D_{50}	Definition
DL_2	Rate of spatial decay of sound pressure per distance doubling
e	Napier's constant
f	Frequency
G	Strength
h	Impulse response
I	intensity
L_{bgA}	A-weighted background noise level
L_n	Step sound level
$L_{n,w}$	Step sound level index
L_p	Sound pressure level
L_{pE}	Sound exposure level
m	Value of modulation transfer function
p	Sound pressure
P	Sound power
r_d	Distraction distance
R	Airborne sound insulation
R_w	Airborne sound insulation index
S	Area
S/N	Signal-to-noise ratio
T_{20}	Reverberation time [(-5 dB - -25 dB) × 3]
T_{30}	Reverberation time [(-5 dB - -35 dB) × 2]
T_{60}	Reverberation time
T_s	Center time
V	Volume
α	Absorption index
θ	Angle of the propagating wave
λ	Wavelength
ρ	Density of the air

Acronyms

EDT	Early decay time
EN	European standard
HAPC	Heating, plumbing, air-conditioning
IEC	International Electrotechnical Commission
ISO	International Organization of Standardization
ITU-T	International Telecommunication Union Standardization Sector
MTF	Modulation transfer function
RASTI	Rapid speech transmission index
SFS	Finnish Standards Association
STI	Speech transmission index
STIPA	Speech transmission index for public address
WHO	World Health Organization

1 Introduction

1.1 Acoustics of public spaces in Finland

Sound environment is an important part of the indoor environment. Sound environment could often be poor in public-type spaces, such as healthcare spaces, offices, and schools. These premises could be overly reverberant making the room uncomfortable to be in, or speech privacy could be poor causing confidential subjects to spread. Or on the contrary, the speech intelligibility could be very low in the spaces where it is important to understand other people's words. Acoustics of these kind of spaces are taken surprisingly poorly into consideration, although people spend half or more of their day inside these spaces.

Old buildings do not necessarily offer acceptable acoustic conditions for cognitively demanding working or for needed privacy. New buildings could satisfy these needs but often acoustics is still not taken into account when designing the building. Furthermore, open spaces are becoming more and more popular among schools and offices due to cost efficiency and aesthetic and modern appearance of the space. Open spaces do not usually offer speech privacy or privacy for concentration. These starting points set challenges for improving the sound environment, without ruining the aesthetic experience of the space.

The urge to improve the sound environments of the spaces is increasing all the time along the knowledge of acoustics. However, usually other basic environmental factors such as temperature, draughtiness, and lightness are first improved before it is acoustics' turn, although the sound environment has been shown to affect to the productivity, concentration, stress level, and healing. Thus, the sound environment should be taken more seriously into account when designing new healthier and more comfortable spaces to people to work and to live in.

Designing concert halls in terms of acoustics has been done since 19th century and manufacturing mineral wool, the basic absorption material, has been started also already at 19th century. Still, treating the public spaces acoustically is not very common. The scope of this thesis is to show the importance of the acoustics in different working and living environments by using existing objective measurement methods.

In this thesis the sound environment of three different types of public-type spaces were studied by objective measurements. The studied spaces were a classroom, a healthcare space, and an open plan office. The classroom was located in the Piikkiö comprehensive school, the healthcare place was patient room in the Seinäjoki hospital, and the open plan office was the bureau of the Finnish Real Estate Federation in Helsinki. The spaces were renovated acoustically and the measurements were conducted before and after the acoustical treatment. The measured spaces were also in normal use or they will be in normal use. From the measurement results the influence of the realized acoustical treatment to the sound environment was considered. The most common room acoustic criteria, such as the reverberation time, speech transmission index, rate of spatial decay of sound pressure level per distance doubling, clarity, and strength, were used to objectively determine the acoustical conditions of the measured spaces and to unravel the changes the acoustical treatment caused. Suggestions for improving the sound environments of the measured spaces even more are also provided.

1.2 Contents of the thesis

The theory part of the thesis includes the Chapters 2 and 3. The measurement part of the work contains the Chapters 4 and 5.

In the second chapter the room- and the building acoustic theory is explained. The room acoustic theory contains the properties of a sound wave and a theory of a sound reflection, refraction, and absorption.

The third chapter consists of descriptions of the most common room acoustic criteria. Room acoustic criteria are used to determine the acoustical condition of the desired space.

The fourth chapter consists of descriptions of acoustics of a classroom, a healthcare space, and an open plan office along with the recommendations for acoustical conditions from different standards and guidelines. Solutions and possibilities to realize certain acoustic conditions are also provided.

Two different measurement equipment sets were used to measure the spaces. The classroom and the healthcare space were measured with the one set of equipment and the open plan office was measured with the other set. The fifth chapter introduces all the measurement devices, methods, and techniques used in this thesis. The measured spaces are also described in the Chapter 5. The descriptions include the states of all three spaces before and after the acoustical treatment and explanations what quantities was measured.

The results and the analysis of the data are presented in the Chapter 6. The discussion and the comparison of the results are also provided along the suggestions to improve the acoustic conditions of the measured spaces.

Finally, the Chapter 7 concludes the content of the thesis and is followed by references and appendices.

2 Room- and building acoustics

This chapter consists of basic theory of acoustics in general, room acoustics theory, and building acoustics theory. In addition, the most common room acoustic criteria are explained.

2.1 Room acoustics

Room acoustics includes the explanation of the sound as a wave motion and properties of a sound wave. Also, the methods how a sound wave interacts with surrounding space are considered.

2.1.1 Properties of sound wave

Sound in general is longitudinal wave motion of air molecules. Sound wave consists of consecutive volumes of pressed air and thinned air. In other words sound wave consists of consecutive pressures and underpressures around normal air pressure (Figure 1).

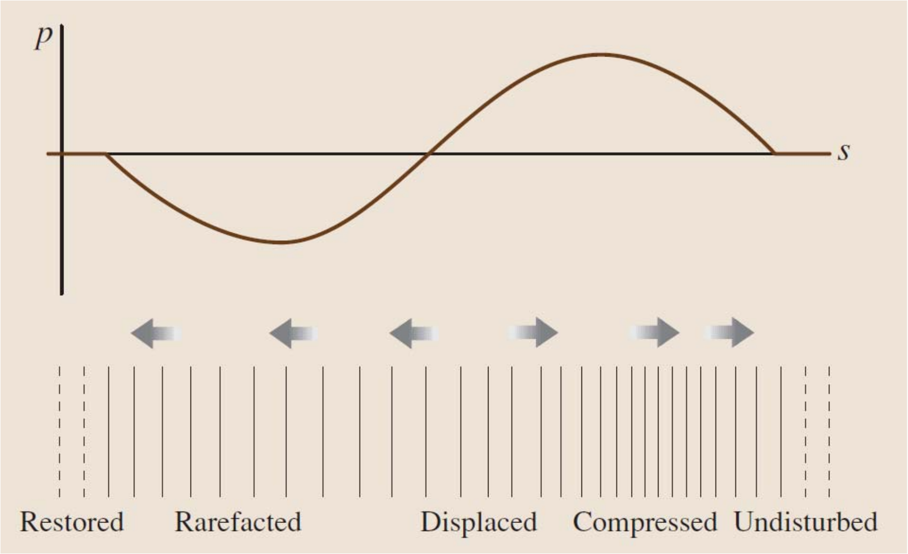


Figure 1: Particle velocity and pressure in one-cycle sinusoidal pulse propagating in the +x-direction. (Rossing 2007)

Sound field in a certain point in space at certain time instant could be determined by measuring the pressure and particle velocity of the sound. Pressure is usually more important measure because changes of pressure arouse the auditory perception in ear and for example the most common acoustical sensor, microphone, is a pressure sensor. Sound pressure is basically the change in the static air pressure. The unit of the pressure is Pascal but the sound pressure is usually expressed in decibel-scale and it is then called sound pressure level:

$$L_p = 10 \log \left(\frac{p^2}{p_0^2} \right) \text{ [dB]}, \tag{1}$$

where p is the sound pressure and p_0 is the reference pressure $p_0 = 20\ \mu$Pa. If energy transmission in sound field is investigated, then the particle velocity should be measured. The particle velocity is the average velocity of the particles in the medium where the wave propagates. For example, when sound wave propagates in the air, the air molecules move back and forth with certain average speed which is the particle velocity (Figure 1). (Lahti 1995; Rossing 2007)

The velocity of the sound wave depends on the medium the wave propagates in. In fluids the velocity also depends on the temperature. Propagation velocity of the sound in air could be expressed as:

$$c = 331.3 + 0.6t \text{ [m/s]}, \tag{2}$$

where t is a temperature in Celsius-degrees (Rossing et al. 2002). For example, in air in 20°C the speed of sound is approximately $c_0 = 343$ m/s. By knowing the speed and the frequency of the sound it is possible to calculate the wavelength of the sound wave:

$$\lambda = \frac{c}{f} \text{ [m]}, \tag{3}$$

where c is the speed of sound and f is the frequency. The frequency of the sound is a physical quantity, which is often referred to a pitch of a sound, but in detail, the pitch is a subjective quantity.

Many acoustical calculations are based on the assumption that the sound wave is a plane wave. The plane wave is a wave where all the wave fronts of the wave are parallel surfaces and are perpendicular to the direction of the propagation. After this point when referring to a sound wave it is assumed to be a plane wave. (Rossing and Fletcher 1995)

2.1.2 Sound reflection and refraction

When sound wave encounters a surface, a part of it will absorb to the obstacle material, a part will penetrate the surface and refract, and the remaining part will reflect from the surface and continue propagation to some other direction. Sound wave reflects from the surface at the same angle as it arrives (Figure 2). The refraction of the sound wave obeys Snell's law:

$$\frac{\sin(\theta_1)}{\sin(\theta_2)} = \frac{c_2}{c_1}, \tag{4}$$

where θ_1 is the angle of the incident wave, θ_2 is the angle of the refracted wave, c_1 is the wave velocity in material 1 (Figure 2) and c_2 is the wave velocity in the material 2 (Figure 2).

Normally the refraction of the sound exists when the temperature of the air changes gradually with the altitude, for example outdoors. This causes the speed of sound to change gradually along the altitude, thus making the sound wave to refract multiple times or in other words to bend. (Karjalainen 2000)

In a normal room the sound wave usually reflects multiple times from different surfaces, for example walls, windows, ceiling, floor, and furniture. If the room has

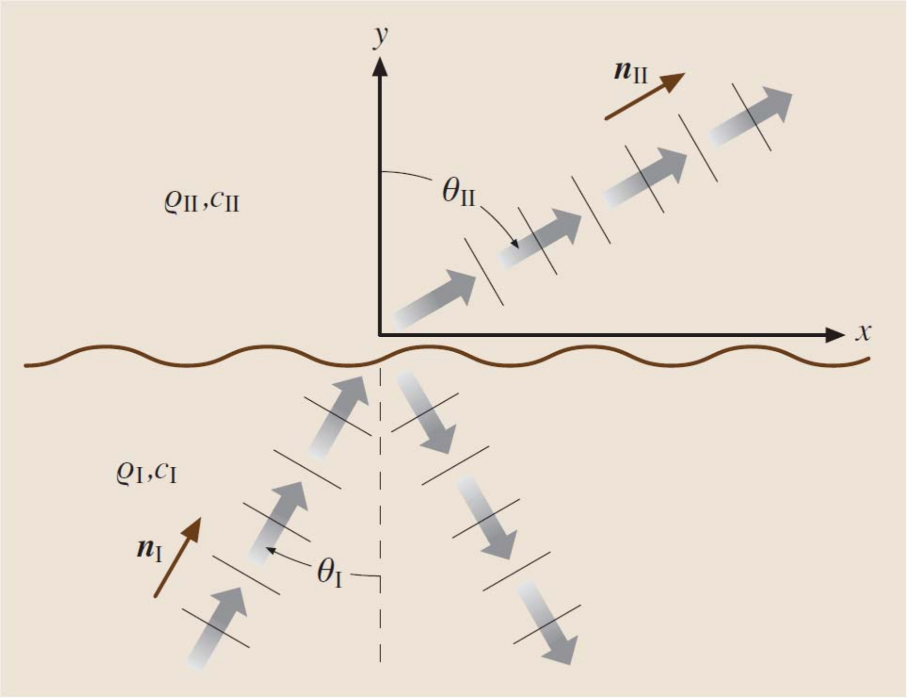


Figure 2: Reflection of a plane wave at an interface between two fluids. (Rossing 2007)

two parallel surfaces (usually opposite walls and floor and ceiling) where the sound is able to reflect, between those surfaces forms a standing wave, which is called a natural vibration or a room mode. The frequency of the room mode depends on the distance of the parallel surfaces. In order to form a mode in a certain frequency, the distance between the parallel surfaces should be an integer multiple of the half of the wavelength of the sound:

$$l_p = n\frac{\lambda}{2} \text{ [m]}, \tag{5}$$

where l_p is the distance between the surfaces, n is the integer coefficient and λ is the wavelength. Using equations 3 and 5 we get the frequency of the formed room mode:

$$f = n\frac{c}{2l_p} \text{ [Hz]}. \tag{6}$$

This basic formula is only true for room modes between two parallel surfaces. (Rossing 2007)

In real rooms exists also other types of room modes. Normal room consists of six surfaces which are parallel in pairs. The above-mentioned one-dimensional case, where the standing wave is formed between two parallel surfaces, is called axial mode. When standing wave is formed between four surfaces it consists of a sum of two standing waves formed between two pairs of surfaces. Thus, it vibrates in two dimensions and it is called tangential mode. The standing wave is called oblique mode when it vibrates in all three dimensions and uses all six surfaces of the room.

The natural frequencies of the desired room could be calculated from formula:

$$f = \frac{c}{2}\sqrt{\left(\frac{l}{L}\right)^2 + \left(\frac{m}{W}\right)^2 + \left(\frac{n}{H}\right)^2}\ \text{[Hz]}, \tag{7}$$

where L, W, and H are the dimensions of the room in meters and l, m, and n are integers describing the degree and the position of the mode. Respectively, the mode frequencies are usually written with three numbers, for example $f(0,1,1)$. Axial modes are obtained from the equation by setting two of the integers l, m, or n zero. Then the Equation 7 reduces to Equation 6. Tangential modes are also obtained from the Equation 7 but now by setting only one of the integers zero. Equation 7 is also only true for rectangular shaped rooms. Usually this does not set any difficulties but it is coming more and more common to use diagonal or tilted walls in buildings just for aesthetic reasons or to avoid flutter echo. If this is the case, then more sophisticated methods, for example computer programs, could be used to model the reflections in rooms. (Uosukainen 2010; Rossing et al. 2002)

In order not to affect to the spectrum of the sound, the room's natural frequencies should be as dense as possible. When examining the Equation 7, it could be noticed that the mode density increases as the frequency increases. Thus, it is usually appropriate to explore only the individual modes at the lower frequencies. Schroeder-frequency is the theoretical limit for considering individual room modes:

$$f_s = 2000\sqrt{\frac{T_{60}}{V}}\ \text{[Hz]}, \tag{8}$$

where T_{60} is the reverberation time of the room and V is a volume of the room. Below the Shroeder-frequency the mode density is so low that individual room modes could be distinguished from each other and thus become significant. Individual modes could affect significantly to the sound pressure level of certain positions in the room, for example if a loudspeaker is placed at the maximum of the mode, the corresponding frequency will be emphasized.

Between two parallel walls is also possible to form a flutter echo. A flutter echo is formed when a sound is reflecting multiple times from the parallel walls and it is perceived as a series of fast consequent echoes. With diffusers, absorption panels or non-parallel walls it is possible to prevent or suppress the flutter echo. (Rossing 2007)

Diffusers are randomly irregular or uneven surfaces. When a sound wave arrives to the diffuser it will reflect to multiple directions, creating more diffuse sound field to the room. This also prevents flutter echoes from developing. Every uneven surface will affect to the diffuseness of the room, and also commercial diffusers are available for treating the room. Totally diffuse sound field does not actually exist, but it is defined as a field which consists of infinite number of plane waves which arrive evenly from every direction and do not correlate with each other. This means that in diffuse field the energy do not flow to anywhere on an average. (Lahti 1995) Many of the basic acoustical measurement- and calculation methods are based on the assumption of the diffuse field. Usually normal rooms could be considered as a diffuse without affecting to the measurement- or calculation results significantly.

2.1.3 Absorption

When a sound wave is absorbed to the material, the acoustical energy is transformed to the heat energy. The sound is transformed to heat because pores of the material generate friction to the particle vibration inside the material. Porous materials, such as mineral wool, have usually a high ratio of absorption. The ratio of absorption is defined as:

$$\alpha = \frac{I_i - I_r}{I_i}, \tag{9}$$

where I_i is the incident intensity and I_r is the reflected intensity as illustrated in Figure 3. (Hongisto 2011)

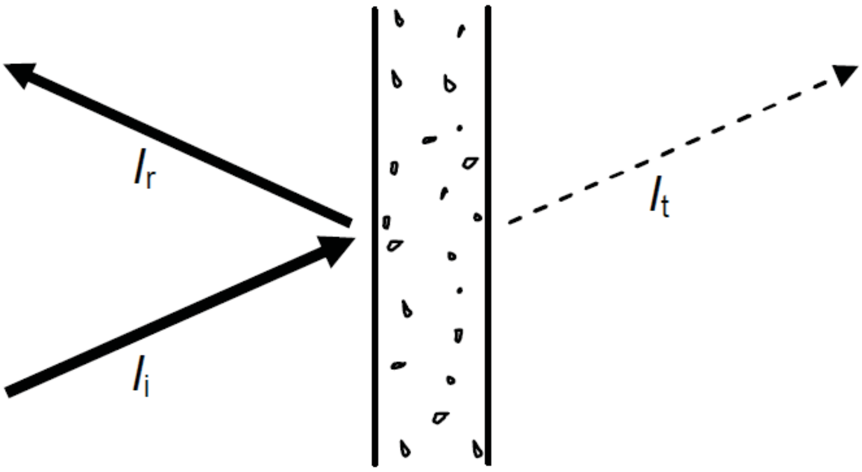


Figure 3: Towards the structure focuses sound intensity I_i, from the structure reflects back sound intensity I_r. To the other side of the structure propagates sound intensity I_t. Adopted from (Hongisto 2011).

The best location to place an absorbent (for example an acoustical panel) is the place where the particle velocity of the sound wave is at maximum, because absorption is based on the motion of the molecules in the absorbent. In normal rooms the sound pressure at the wall is at the maximum and the particle velocity at the minimum. The maximum point of the particle velocity is at the quarter a wavelength from the wall. Thus, the absorption panel should be as thick as quarter a wavelength of the desired frequency. At lower frequencies this could be impossible. For example, when $f = 50$ Hz, $\lambda/4 = 1.7$ m, but already at 500 Hz the wavelength is only 17 cm. All the higher frequencies will of course absorb to the panel and also the lower frequencies to some extent. Tolerable absorption is achieved already when the thickness of the absorption material is only one tenth of the wavelength (Figure 4). (Taina 2006)

2.2 Building acoustics

Building acoustics includes explanations of airborne sound insulation and step sound insulations. In addition, sound emanating in buildings is considered.

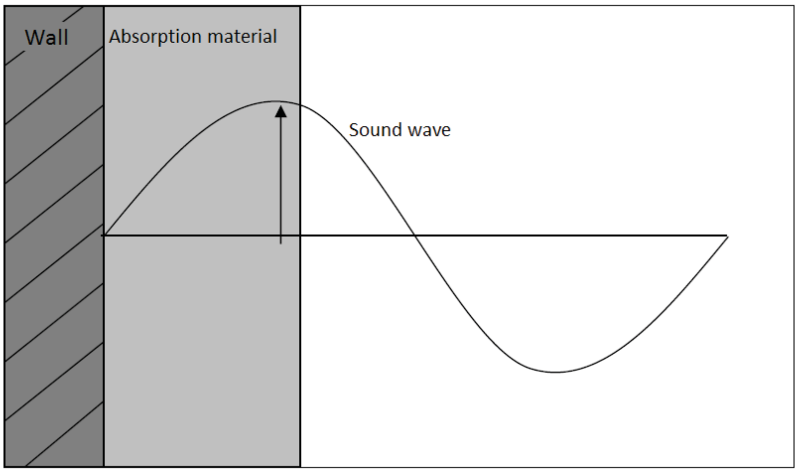


Figure 4: A sound wave hitting to the wall, which contains additional absorption material. Adopted from (Taina 2006).

2.2.1 Airborne sound insulation

Airborne sound insulation describes different construction components', such as outdoor walls', partition walls', and floors', or individual elements', such as windows', doors', and ventilators' ability to insulate noise. The physical quantity of sound insulation is expressed as:

$$R = 10 \log \frac{P_i}{P_t} \text{ [dB]}, \tag{10}$$

where P_i is the incident sound power focusing on the investigated structure and P_t is the transmitted sound power. (Lahti 1995)

The sound insulation could be measured in situ or in a specific laboratory. The in situ measured values of sound insulation are usually considerably lower than values measured in the laboratory. The main reason to that is the flanking transmission, where the sound propagates through the measured component but also around it for example via the frame of the building. The part of the penetrated sound and the part of the flanking transmission is impossible to determine. The accuracy of the measurement is also usually lower when performed in the field. (Lahti 1995)

Airborne sound insulation is measured in the laboratory which consists of two adjacent rooms where the measured component is in between the rooms (Figure 5). The first room is a transmission room and the second room is a receiver room. In the transmission room a loudspeaker emits broadband or bandwidth-limited noise and produces incident sound power P_i to the measured surface. In the receiver room the investigated sound penetrable surface acts as a sound source and the penetrated sound power is finally absorbed in the surfaces of the room. The incident sound power could be calculated from the equation:

$$P_i = \frac{\langle p_1^2 \rangle}{4\rho c} S \text{ [W]}, \tag{11}$$

where $\langle p_1^2 \rangle$ is a spatial average of the squared sound pressure in transmission room (1), ρ is the density of the air, c is the velocity of the sound in the air, and S is the area of the investigated component. The transmitted sound power equals to the absorbed sound power in receiver room (2):

$$P_t = \frac{\langle p_2^2 \rangle}{4\rho c} A \ [\mathrm{W}], \tag{12}$$

where A is the absorption area of the receiver room. From these equations we get the basic formula for the sound insulation:

$$R = 10 \log \left(\frac{\langle p_1^2 S \rangle}{\langle p_2^2 A \rangle} \right). \tag{13}$$

When the spatial averages of the squared sound pressures are replaced with the corresponding average sound pressure levels (L_1 and L_2) in rooms 1 and 2, the Equation 13 reduces to:

$$R = L_1 - L_2 + 10 \log \left(\frac{S}{A} \right). \tag{14}$$

Now the absorption area of the receiver room could be determined by measuring the reverberation time of the room (see Section 3.1) and the equation reduces further to:

$$R = L_1 - L_2 + 10 \log S - 10 \log \left(0.161 \frac{V}{T} \right), \tag{15}$$

where the Sabine's formula (Equation 18) is used. (Lahti 1995; Hongisto 2011)

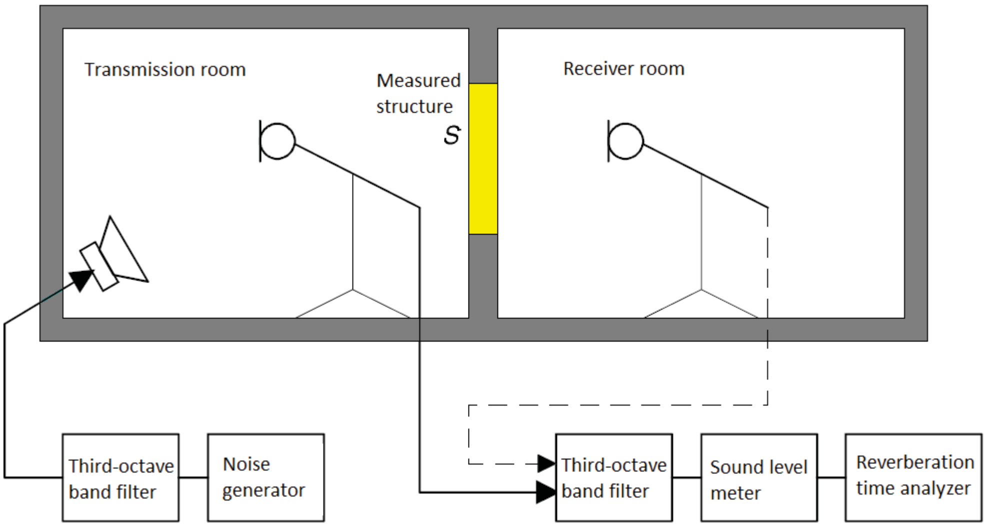
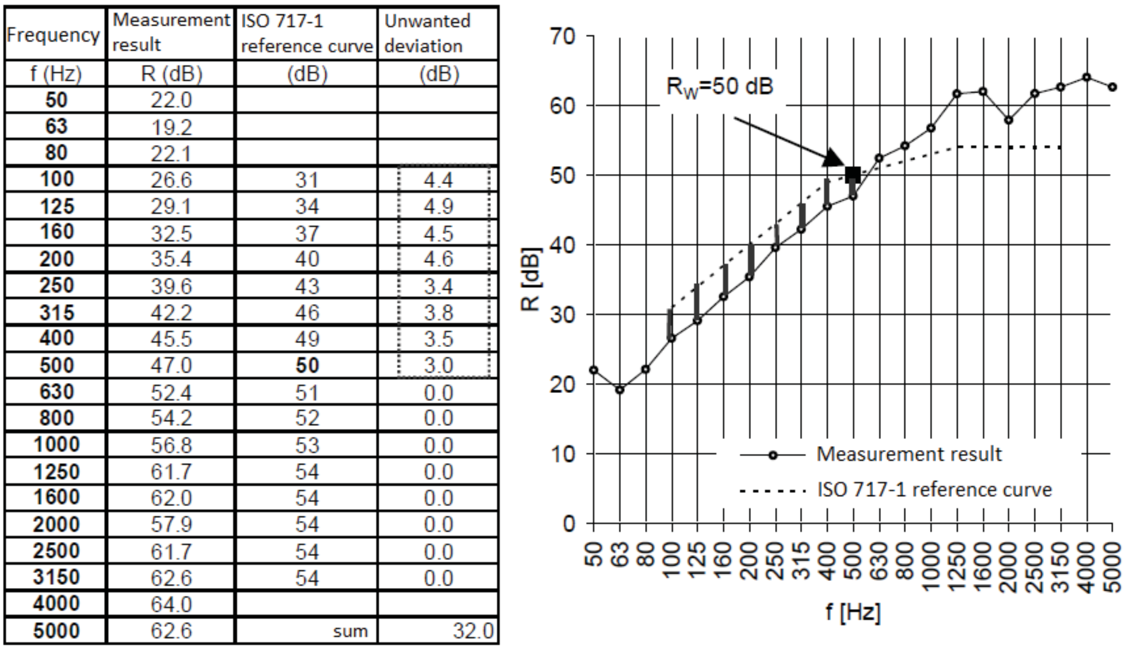


Figure 5: Sound insulation measurement laboratory. Adopted from (Lahti 1995).

Sound insulation depends on the frequency and is usually measured in five or seven whole octave bands. The large number of measured values are the reason why airborne sound insulation index R_w has been developed. It represents the construction component's ability to insulate sound with a single value and it is based on international standard ISO 717-1: *Acoustics. Rating of sound insulation in buildings and of building elements. Part 1: Airborne sound insulation.* The airborne sound insulation index is determined by fitting a certain reference curve (defined in ISO 717-1) to the measured sound insulation curve (Figure 6) and then taking the value of the reference curve from 500 Hz point. The fitting is done by moving the reference curve in 1 dB steps until the sum of the unwanted deviations decreases below 32.0 dB. The unwanted deviations are the points where the values of measured sound insulation go below the corresponding points at the reference curve (illustrated with black vertical lines in Figure 6). The shape of the reference curve is always the same, only the vertical position is changed in the procedure. If the airborne sound insulation index is measured in the field, it is expressed as R'_w. (Hongisto 2011; ISO 717-1:1996 1996; Hirvonen 2007a)



Frequency	Measurement result	ISO 717-1 reference curve	Unwanted deviation
f (Hz)	R (dB)	(dB)	(dB)
50	22.0		
63	19.2		
80	22.1		
100	26.6	31	4.4
125	29.1	34	4.9
160	32.5	37	4.5
200	35.4	40	4.6
250	39.6	43	3.4
315	42.2	46	3.8
400	45.5	49	3.5
500	47.0	**50**	3.0
630	52.4	51	0.0
800	54.2	52	0.0
1000	56.8	53	0.0
1250	61.7	54	0.0
1600	62.0	54	0.0
2000	57.9	54	0.0
2500	61.7	54	0.0
3150	62.6	54	0.0
4000	64.0		
5000	62.6	sum	32.0

Figure 6: The determination of the sound insulation index R_w. The dashed line is the ISO 717-1 reference curve and it is placed to the highest possible position where the sum of unwanted deviations is below 32.0 dB. The value of R_w is taken from the reference curve at 500 Hz. An unwanted deviation happens when measured value is below the reference curve (black vertical lines). Adopted from (Hongisto 2011).

The sound insulation of a thin slab, for example a wall panel, could be divided into five regions in frequency domain (Figure 7). In the first part the frequency is so low that no eigenmodes exist. In the second part exists the first eigenmode and the sound insulation of the panel is weak because of the resonance. The third region consists of modes and some forced oscillation occurs. Its sound insulation depends mainly of the mass per area of the panel. In part four is located the threshold frequency of the coincidence. In that frequency the velocity of the wave oscillating in the panel equals to the velocity of the airborne sound wave and the airborne sound wave couples to the panel and penetrates it perfectly. It means that the sound insulation in that frequency region is very low. Above the threshold frequency of coincidence the stiffness of the panel is dominating and only eigenmodes exist.

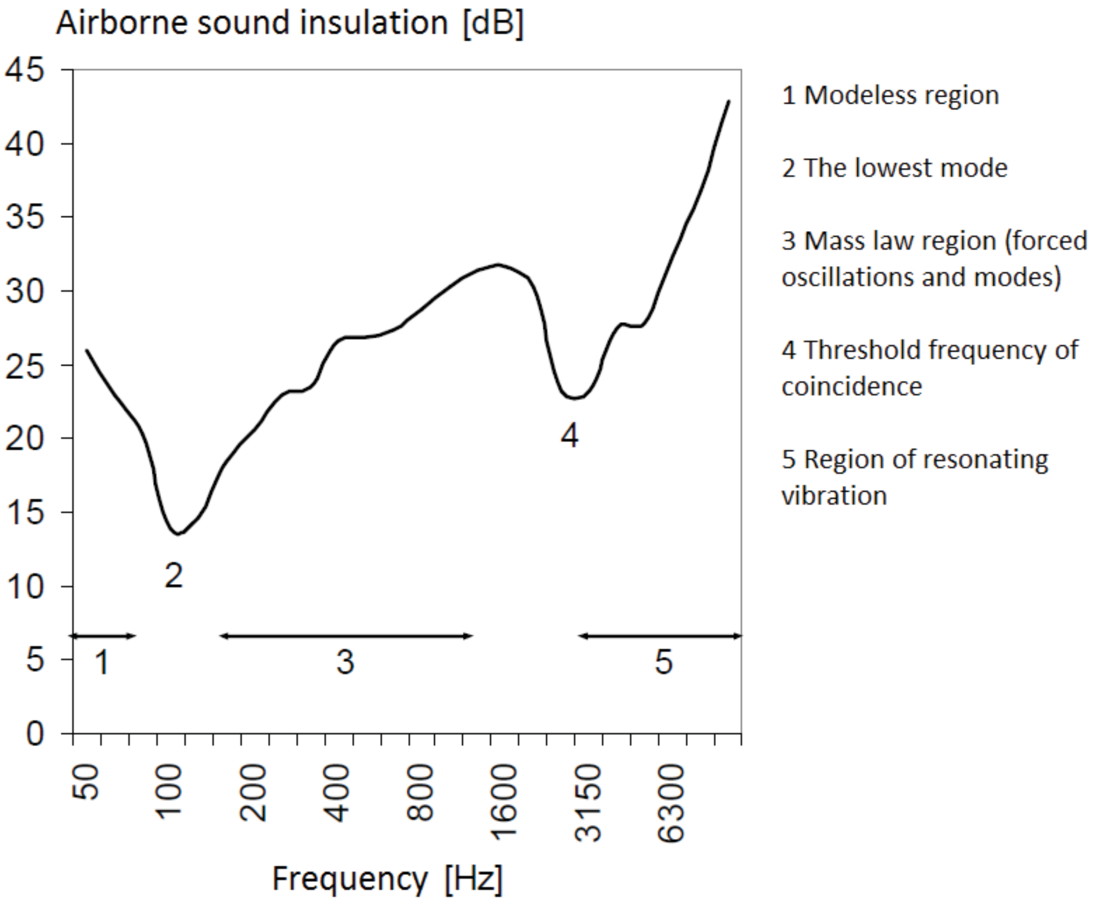


Figure 7: The behaviour of the sound insulation of a thin slab in different frequency regions. Adopted from (Hongisto 2011).

A twofold wall structure is a good choice when a better sound insulation is wanted. The twofold wall structure means that two individual panels are assembled one after another, the way that an air gap is formed between the panels. The air gap could contain absorption material and supporting studs as in partition walls, but it could also be totally empty like windows usually are.

Normally, the different sides of the twofold wall structure are in mechanical connection with each other via metallic or wooden studs and rails. Then the structure is called coupled structure. If the halves of the structure are completely isolated from each other the structure is called uncoupled structure. This kind of structure makes very high sound insulation values possible.

The sound insulation of the uncoupled structure improves when total mass is increased, the thickness of the air gap is increased, and when the amount or absorption index of the absorption material in the air gap is increased. The same rules are also true for coupled structures but in much smaller scale. The characteristics of the coupling structures mainly affects to the sound insulation of the coupled structure.

For example, the influence of the amount of the absorption material is negligible if the studs are wooden. The sound insulation of the coupled structure is increased when the number of studs or rails decreases, the dynamical stiffness of the studs is decreased (the flexibility of the studs is increased), and when the attaching of the panels to the studs gets weaker (the number of screws is decreased or the tightness of the screws is decreased). (Hongisto 2011; Hirvonen 2007a)

2.2.2 Step sound insulation

Step sounds are structure-borne noises which are produced by walking, dropping objects to the floor, or moving furniture etc. When the structure experiences this kind of hit it gets the surrounding air to vibrate and the hit could be perceived as an airborne sound in the other side of the structure.

Unlike airborne sound insulation, step sound insulation is an absolute quantity because it is determined by using a calibrated sound source, thus determining the output power is unnecessary. The sound source is standardised step sound device, which creates the step-like sounds by dropping 0.5 kg hammers to the floor from 40 mm height 10 times per second. The sound pressure level in the other space caused by the step sound device is measured in desired frequency bands. Thus, the step sound insulation of the measured structure is the better the lower the measured sound pressure levels are. Usually the sound pressure levels are measured in a space below the space where the step sound device is, but sometimes it is necessary to measure the pressure levels above or next to the transmitting room.(Hongisto 2011; ISO 140-7:1998 1998; Hirvonen 2007a)

The quantity used to describe the step sound insulation is normalized step sound level:

$$L_n = L_2 + 10 \log \frac{A_2}{A_0} \text{ [dB]}, \tag{16}$$

where L_2 is the measured equivalent sound pressure level in the receiver room, A_2 is the absorption area of the receiver room, and A_0 the reference absorption area $A_0 = 10\ \text{m}^2$. The smaller the step sound level the better the step sound insulation. The absorption area of the receiver room could be determined by measuring the reverberation time of the room (see Section 3.1).

Like airborne sound insulation the step sound insulation could also be expressed with one-number quantity, step sound level index $L_{n,w}$. The method to determine the index is similar as with the airborne sound insulation. The reference curve is again moved to the position where the sum of the unwanted deviations is 32 dB at maximum. Then the value of $L_{n,w}$ is read from the reference curve at 500 Hz point. This time the unwanted deviation occurs when the measured sound pressure level is above the reference curve. (ISO 717-2:1996 1996; Hirvonen 2007a)

The real step sounds and the sounds created by the step sound device do not correspond very well, thus the spectral weighting factor C_I is created. In standard ISO 717-2: *Acoustics. Rating of sound insulation in buildings and of building elements. Part 2: Impact sound insulation* C_I is defined in frequency bands 100 Hz - 2500 Hz and $C_{I,50-2500}$ in frequency bands 50 Hz - 2500 Hz. $C_{I,50-2500}$ is calculated from measured and normalized sound pressure levels and step sound level index as follows:

$$C_{I,50-2500} = 10 \log \sum_{i=50}^{2500} 10^{L_{n,i}/10} - 15 - L'_{n,w} \text{ [dB]}, \tag{17}$$

where $L_{n,i}$ are measured step sound levels in different frequency bands, and $L'_{n,w}$ is the step sound level index. The sum of the step sound level index and spectral weighting factor $L'_{n,w} + C_{I,50-2500}$ is discovered to be more equivalent to subjective experience of the step sound insulation than the step sound level index alone. (Hongisto 2011; Hirvonen 2007a)

2.2.3 Sound emanating in buildings

The measured sound insulation of a structure between two rooms in a building is practically always lower than the corresponding value measured in the laboratory. The reason to this is that sound emanates to the other room straight through the structure dividing the rooms but also along the other structures and junctions around the room (Figure 8). The sound emanates in frame of the building as a structure-borne sound. The sound could also emanate through the pipes, wires, and air conditioning pipes.

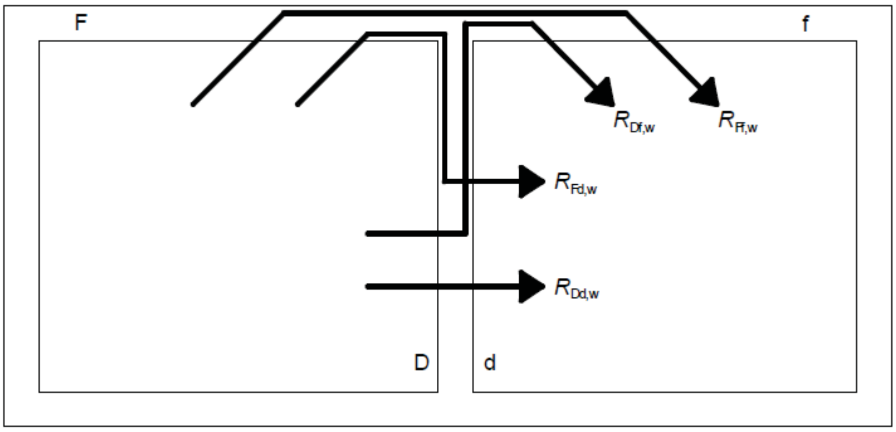


Figure 8: The different paths of emanating sound through only one junction. (Hirvonen 2007a)

Flanking transmission means all the transmission paths of the sound, which do not go directly through the structure dividing the spaces. Also, the holes or cracks in the structure weakens the sound insulation, but these are either design or construction mistakes and could usually be treated afterwards.

Structure-borne sound attenuates mainly in the junctions of the different structures. The attenuation depends on the mass of the structures and the stiffness of the junctions. Additionally, the structure-borne sound could be attenuated by creating joints to the structures, where the structure is cut with for example air or mineral wool layer. (Hongisto 2011; Hirvonen 2007a)

3 Room acoustic criteria

Room acoustic criteria are objective quantities which could be measured to determine the acoustical conditions of the space. Each criterion represents a different acoustical property of the measured space. Multiple criteria are used together to determine the acoustics of the space, as none of the criteria alone could describe the acoustics diverse and accurate enough.

3.1 Reverberation time (T_{60})

When a sound source emits a sound in a room, creating a certain sound field and sound pressure level in the room, and is suddenly stopped, sound pressure level starts to decrease. Within a certain amount of time the sound pressure level has decreased 60 dB (to one millionth) from the original level. This time is called a reverberation time, T_{60}. The above described definition of the the reverberation time is also illustrated in Figure 9. The reverberation time is a property of the envelope of the impulse response of the acoustic system consisting of a sound source and a room. (Lahti 1995) The reverberation time is probably the most commonly measured acoustical parameter when analysing acoustical behaviour of the room.

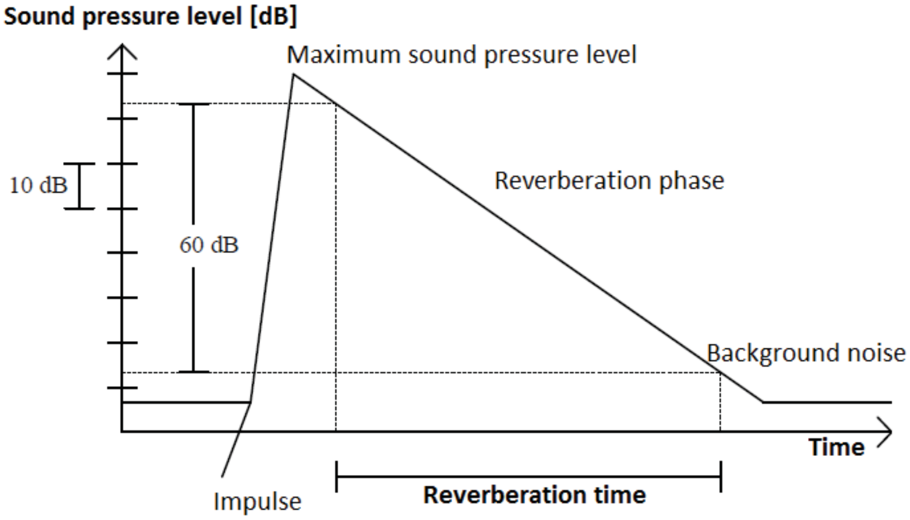


Figure 9: Definition of the reverberation time T_{60}. (Hongisto 2011)

W. C. Sabine has developed the equation which describes the relation of the reverberation time, the volume and the absorption area of the room:

$$T_{60} = 0.161\frac{V}{A}\ [\mathrm{s}], \tag{18}$$

where T_{60} is the reverberation time, V is a volume of the room and A is an absorption area of the room, which is defined with equation:

$$A = \sum_{i=1}^{n} \alpha_i S_i\ [\mathrm{m}^2], \tag{19}$$

where α_i are absorption ratios of the materials in the room and S_i are areas of the corresponding materials. Ideally the Equation 18 is accurate in the diffuse field only. In practice, rooms which are not too large or complicated and contain only small amount of absorptive materials can be considered as diffuse. (Lahti 1995)

The impulse response of the ideal room is decaying exponentially and T_{60} could be determined from the envelope of the room's impulse response. Often the signal-to-noise ratio is not high enough to obtain the whole 60 dB drop on the decay curve. Therefore the value of T_{60} is normally achieved by measuring the decay time between -5 dB and -35 dB and multiplying it by two or between -5 dB and -25 dB and multiplying it by three. To distinguish the different calculation methods, T_{60} is sometimes called T_{30} or T_{20} correspondingly. These methods are illustrated in Figure 10. The reverberation time can be calculated from the total impulse response of the room or for example octave band filtered responses. In the first case the reverberation time represents the average decay time of the room and in the latter case it represents the decay time on desired frequency band. Reverberation times in different frequency bands could vary significantly. (Lahti 1995)

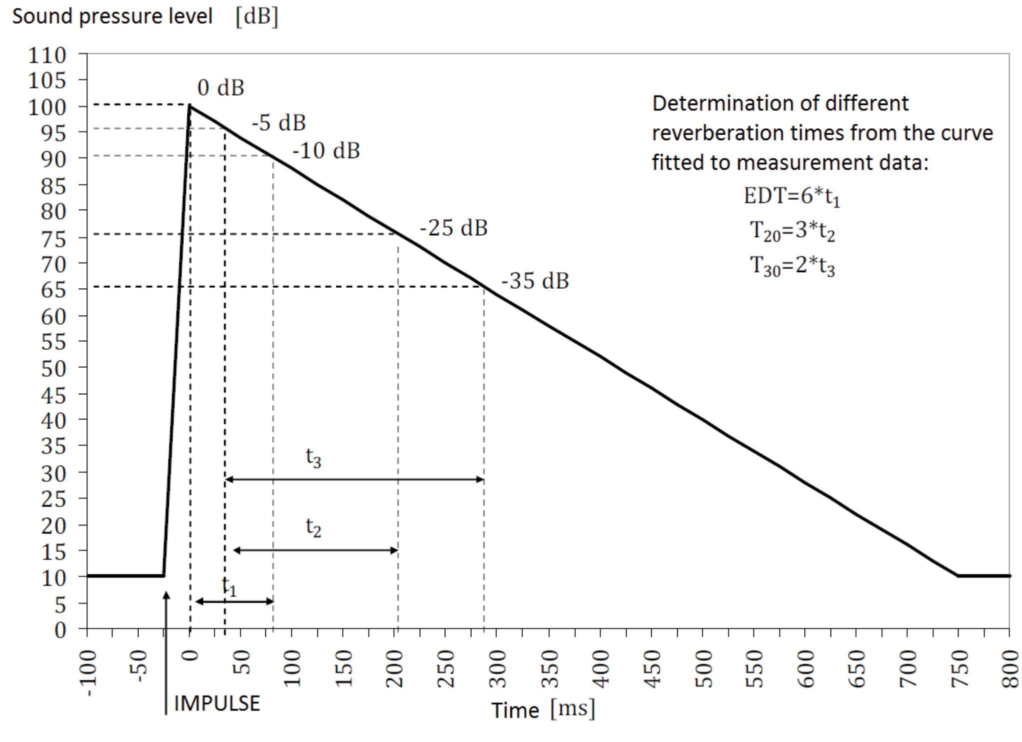


Figure 10: Definitions of different methods to determine the reverberation time. Adopted from (Hirvonen 2007a).

A few different methods exists to select the points (for example -5 dB and -35 dB) from the decay curve. The simplest way is to just pick those two individual points from the decay curve and calculate the time elapsed between them. However, that method depends largely on the shape of the curve and varies significantly between different measurements due to the noisiness of the signal. Second method is to fit a line to the decay curve using for example the least squares method and to pick the corresponding points from that line (Figure 11). Now the line represents more average value of the curve than two individual points. The third and the most accurate method is to use backwards integration, called Schroeder-integration:

$$L(t) = 10 \log \left(\frac{\int_t^\infty h^2(\tau) d\tau}{\int_0^\infty h^2(\tau) d\tau} \right) \text{[dB]}, \tag{20}$$

where h is a measured impulse response. Schroeder-integration is based on the relationship between the ensemble average of all possible individual decay curves and the corresponding impulse response:

$$\langle y^2(t) \rangle_e = \int_t^\infty |h(\tau)|^2 d\tau = \int_0^\infty |h(\tau)|^2 d\tau - \int_0^t |h(\tau)|^2 d\tau, \tag{21}$$

where $\langle y^2(t) \rangle_e$ is the time average of the squared decay curves and $h(\tau)$ is the impulse response of the system. (Schroeder 1965)

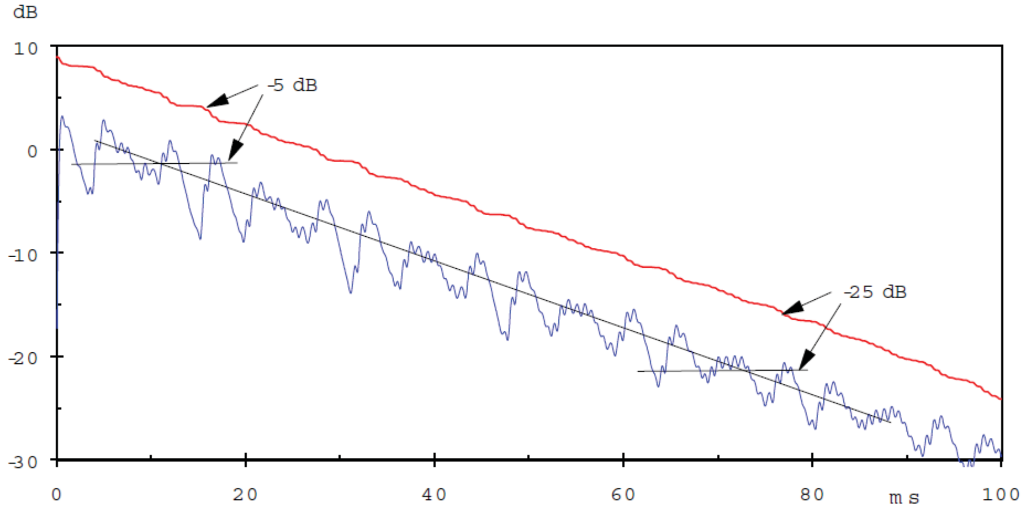


Figure 11: Determining the reverberation time with ordinary root-mean-square detector and fitted line (lower curve) and determining the reverberation time with Schroeder-integration -method (upper curve). (Lahti 1995)

In Schroeder-integration the impulse response is integrated backwards from 5 dB above the noise floor of the decay curve to the beginning of the direct sound (Figure 11). The obtained curve is much smoother that the original decay curve and a line could again be fitted to the curve using the least squares method and then the two points could be picked from the line. (Lahti 1995; Peltonen 2000)

3.2 Early decay time (EDT)

Early decay time (EDT) is a similar quantity as T_{60} and it is determined with the same methods from the decay curve. The difference between EDT and T_{60}

is the evaluation interval. EDT is determined on the decay curve from 0 dB to -10 dB and then multiplied by six (Figure 10). (Jordan 1970) In ideal exponential decay -case EDT equals to T_{60}. Measured values of EDT have a larger variance than corresponding values of T_{60} because the first reflections can differ significantly depending on measurement position. Also, the short integration period makes EDT more vulnerable to errors and accurate determination of the direct sound more important. (Peltonen 2000)

EDT considers the early part of the reverberation, including the first distinct reflections, which have more subjective importance to perceived reverberance than the late part (Barron 1995). If the value of EDT is high, it indicates much reverberation and low clarity. Correspondingly, if the value of EDT is low it indicates more clarity and less reverberation. EDT is also used when calculating the speech transmission index (Section 3.3).

3.3 Speech transmission index (STI, RASTI and STIPA)

Speech transmission index (STI) is an objective measure of a speech intelligibility between a speaker and a listener. The distinctness and thus the intelligibility of the speech in a room depends on the ratio of the background noise and the level of the speech, reverberation time, the distance between the speaker and the listener, and the directivity and the orientation of the speaker. (Hongisto 2011)

STI is a number which represents the quality of the speech transmission when considering syllabic distinctness. The value of the STI can vary between 0.00 and 1.00. The higher the value the better the syllabic distinctness is. Value of 1.00 represents the perfect speech transmission channel between the speaker and the listener and value of 0.00 respectively represents the worst possible case, where not a single syllable from the speak is possible to understand. (Hongisto 2011; Karjalainen 2008)

It has been shown that to the intelligibility of the speech mainly affects the reverberation time and the background noise of the room. From this starting point the concept of the modulation transfer function (MTF) has been developed. The MTF is used to characterize the sound transmission system by sending a test signal through the speaker to listener -system and inspecting the reduction of the modulation index of the intensity envelope of the travelled signal relative to the corresponding index of the original signal. The test signals used with modulation transfer function are basically octave band filtered sine wave modulated noise. Test signals are used in seven octave bands (125, 250, 500, 1000, 2000, 4000, and 8000 Hz) and also 14 different modulation frequencies are used (0.63, 0.80, 1.00, 1.25, 1.60, 2.00, 2,50, 3.15, 4.00, 5.00, 6.30, 8.00, 10.00, and 12.50 Hz). These octave bands represent the frequency band of the normal speech and the modulation frequencies represent the temporal variations of the normal speech. (Houtgast and Steeneken 1985) The value of the modulation transfer function could be calculated from the equation:

$$m(F,f) = \frac{1}{\sqrt{1+[T(f)2\pi F/13.8]^2}} \cdot \frac{1}{1+10^{[-S/N(f)]/10}}, \tag{22}$$

where $T(f)$ is the early decay time (EDT, see Section 3.2) in a certain frequency band f, F is the modulation frequency, and S/N is the signal-to-noise ratio ($S/N = L_s - L_N$, where L_s is the level of the signal and L_N is the level of the noise) of the room in a certain frequency band. It could be seen that the Equation 22 consists of two parts. The first part represents the effect of the reverberation time and the latter part represents the effect of the background noise to the MTF. From Equation 22 is possible to calculate 98 different m-values (one for each octave band and modulation frequency combination).

To obtain the STI-value, the m-values calculated from the Equation 22 should be converted to apparent signal-to-noise ratios $(S/N)'$ with equation:

$$S/N' = 10 \log \left(\frac{m}{1-m} \right) \text{ [dB]}. \tag{23}$$

If $S/N' > 15$ dB, $S/N' = 15$ dB. Correspondingly if $S/N' < -15$ dB, $S/N' = -15$ dB. After this the STI-value could be calculated from the equation:

$$STI = \frac{1}{30} \left\{ 15 + \sum_{j=1}^{7} w_j \left[\frac{1}{14} \sum_{i=1}^{14} S/N'(F_i, f_j) \right] \right\}, \tag{24}$$

where the weight factors w_j of the octave bands are 0.13, 0.14, 0.11, 0.12, 0.19, 0.17, and 0.14. The latter part of the equation is simply the weighted mean of the apparent signal-to-noise ratios. The STI's dependencies on the background noise and the reverberation time are illustrated in Figures 12 and 13. STI-values could be classified to five different classes, whose names verbally describe the quality of the speech intelligibility. The classes are presented in Table 1. (Hongisto 2011)

Table 1: Speech intelligibility quality based on STI-value. (IEC 60268-16:1988 1988)

STI value	**Quality**
0.00 - 0.30	bad
0.30 - 0.45	poor
0.45 - 0.60	fair
0.60 - 0.75	good
0.75 - 1.00	excellent

RASTI (Rapid speech transmission index) is a reduced version of STI. RASTI was developed for more convenient measurement procedure, as measuring STI was fairly time consuming because all the 14 modulation frequencies should be determined in all the 7 octave bands. When using RASTI, only two octave bands (500 Hz and 2000 Hz) and nine modulation frequencies (1.00 Hz, 2.00 Hz, 4.00 Hz, and 8.00 Hz in 500 Hz band and 0.70 Hz, 1.40 Hz, 2.80 Hz, 5.60 Hz, and 11.2 Hz in 2000 Hz band) are used. RASTI substantially reduced the measurement time of the STI.

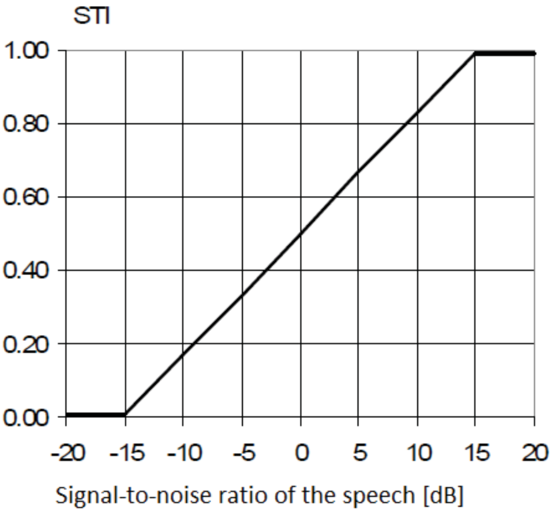


Figure 12: STI's dependency of the signal-to-noise ratio of the speech L_{SN}, assuming that the space is anechoic and the signal-to-noise ratio is frequency independent. (Hirvonen 2007a)

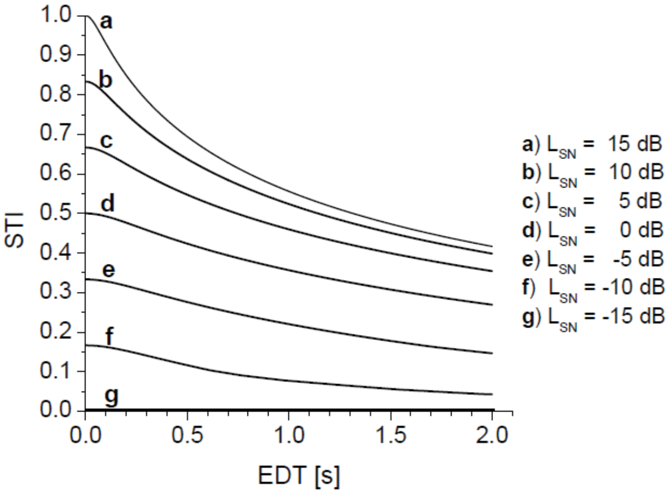


Figure 13: STI's dependency of the early decay time and of the signal-to-noise ratio of the speech L_{SN}, assuming both frequency independent. (Hirvonen 2007a)

However, RASTI has proven to be rather unreliable when comparing to STI. (Mapp 2005)

STIPA (Speech transmission index for public address) is also a reduced version of STI. Originally STIPA was developed for testing the quality of the public address systems, but it has later proven to be quite an accurate version of STI. In Figure 14 is compared the calculated values of the STI and STIPA values. From the figure could be seen that the correspondence between STI and STIPA is nearly perfect. Standard IEC 60268-16 describes a STIPA-method which uses six octave bands and 12 modulation frequencies. The 125 Hz and 250 Hz octave bands are combined and

1.60 Hz and 8.00 Hz modulation frequencies are omitted. The largest difference to STI is that only two modulation frequencies is used for each octave band. In Table 2 is a comparison of the usage of the octave bands and modulation frequencies in STI, RASTI, and STIPA. When using STIPA a dedicated test signal is used. The test signal consists of octave band filtered amplitude modulated noise. According to IEC 60268-16 the test signal should be played from the source which directivity is as close as possible to a real human head. IEC 60268-16 recommends using a loudspeaker which cone diameter is at most 100 mm and refers to the artificial mouth described in ITU-T Recommendation P.51 (ITU-T P.51 1996). However, a new ISO-standard considering open plan offices produces instructions for using omnidirectional sound source instead, because the direction of a talking person at a workstation is not constant and the orientation of the source affects the result quite little. (ISO 3382-3:2012 2012; Hongisto et al. 2007) By recording the test signal at desired positions the STIPA could be calculated with the method described above (equations 22, 23, and 24).

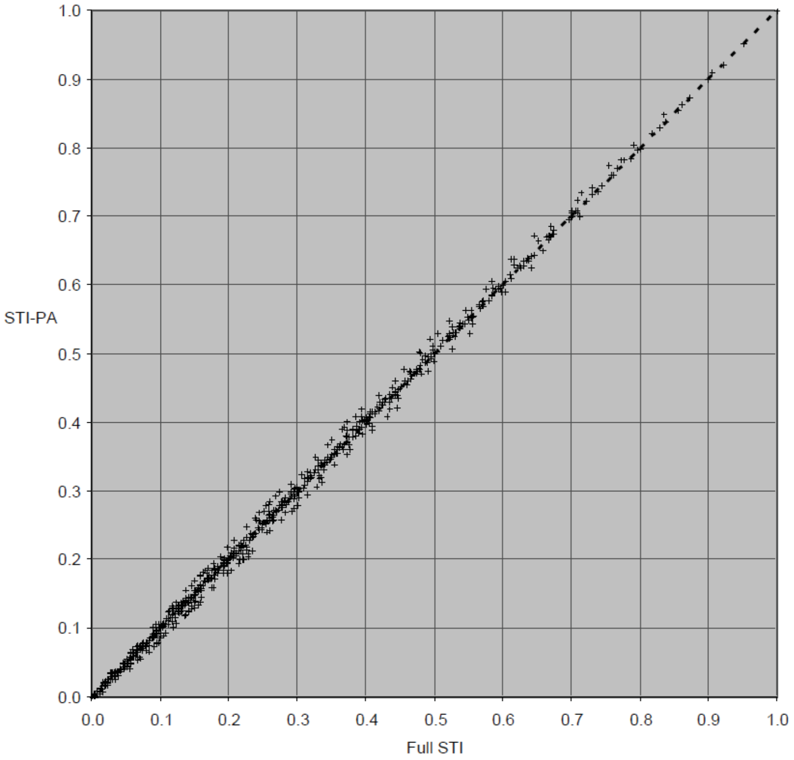


Figure 14: STI values calculated using STIPA excitation signal compared to STI values calculated using the full 98 combinations of modulated noise. (Steeneken et al. 2001)

Distraction distance (r_D) is a measure related closely to STI. It describes how many meters from the speaker the distraction, caused by the speech, is significant. The distraction distance is obtained from the STI versus distance -curve, at the point where the value of STI falls below 0.50. (ISO 3382-3:2012 2012)

Table 2: Comparison of the usage of the frequency bands and modulation frequencies of the different STI measuring methods (STI, RASTI and STIPA).

<table>
<tr><th colspan="15">STI</th></tr>
<tr><th rowspan="2">Octave band</th><th colspan="14">Modulation frequency (Hz)</th></tr>
<tr><th>0.63</th><th>0.80</th><th>1.00</th><th>1.25</th><th>1.60</th><th>2.00</th><th>2.50</th><th>3.15</th><th>4.00</th><th>5.00</th><th>6.30</th><th>8.00</th><th>10.00</th><th>12.50</th></tr>
<tr><td>125 Hz</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td></tr>
<tr><td>250 Hz</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td></tr>
<tr><td>500 Hz</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td></tr>
<tr><td>1000 Hz</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td></tr>
<tr><td>2000 Hz</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td></tr>
<tr><td>4000 Hz</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td></tr>
<tr><td>8000 Hz</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td><td>●</td></tr>
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<table>
<tr><th colspan="15">RASTI</th></tr>
<tr><th rowspan="2">Octave band</th><th colspan="14">Modulation frequency (Hz)</th></tr>
<tr><th>0.63</th><th>0.80</th><th>1.00</th><th>1.25</th><th>1.60</th><th>2.00</th><th>2.50</th><th>3.15</th><th>4.00</th><th>5.00</th><th>6.30</th><th>8.00</th><th>10.00</th><th>12.50</th></tr>
<tr><td>125 Hz</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
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<tr><td>8000 Hz</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
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<table>
<tr><th colspan="15">STIPA</th></tr>
<tr><th rowspan="2">Octave band</th><th colspan="14">Modulation frequency (Hz)</th></tr>
<tr><th>0.63</th><th>0.80</th><th>1.00</th><th>1.25</th><th>1.60</th><th>2.00</th><th>2.50</th><th>3.15</th><th>4.00</th><th>5.00</th><th>6.30</th><th>8.00</th><th>10.00</th><th>12.50</th></tr>
<tr><td>125/250 Hz</td><td></td><td></td><td>●</td><td></td><td></td><td></td><td></td><td></td><td></td><td>●</td><td></td><td></td><td></td><td></td></tr>
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<tr><td>2000 Hz</td><td></td><td></td><td></td><td>●</td><td></td><td></td><td></td><td></td><td></td><td></td><td>●</td><td></td><td></td><td></td></tr>
<tr><td>4000 Hz</td><td></td><td>●</td><td></td><td></td><td></td><td></td><td></td><td></td><td>●</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>8000 Hz</td><td></td><td></td><td></td><td></td><td></td><td></td><td>●</td><td></td><td></td><td></td><td></td><td></td><td></td><td>●</td></tr>
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3.4 Rate of spatial decay of sound pressure level per distance doubling (DL_2)

Spatial decay rate of sound pressure level per distance doubling (DL_2) is a measure which represents the attenuation of the sound when distance from the source is increasing:

$$DL_2 = L_p(r_1) - L_p(r_2) \text{ [dB]}, \tag{25}$$

where $L_p(r_1)$ and $L_p(r_2)$ are sound pressure levels in certain positions and $r_2 = 2r_1$. DL_2 could also be achieved by determining the slope of the spatial sound distribution curve. Curve of spatial sound distribution of the sound pressure level is determined by measuring sound pressure levels of the A-weighted pink noise in different distances from the source and plotting the results to a sound pressure level versus logarithmic distance scale (Figure 15). When using logarithmic distance scale the curve should be linear, as the decay of the sound pressure is supposed to be exponential. The A-weighted pink noise is used because its frequency spectrum is similar to the spectrum of normal speech. The accurate value of the slope of the spatial sound distribution curve should be calculated by fitting a line to the measurement points using the least squares method.

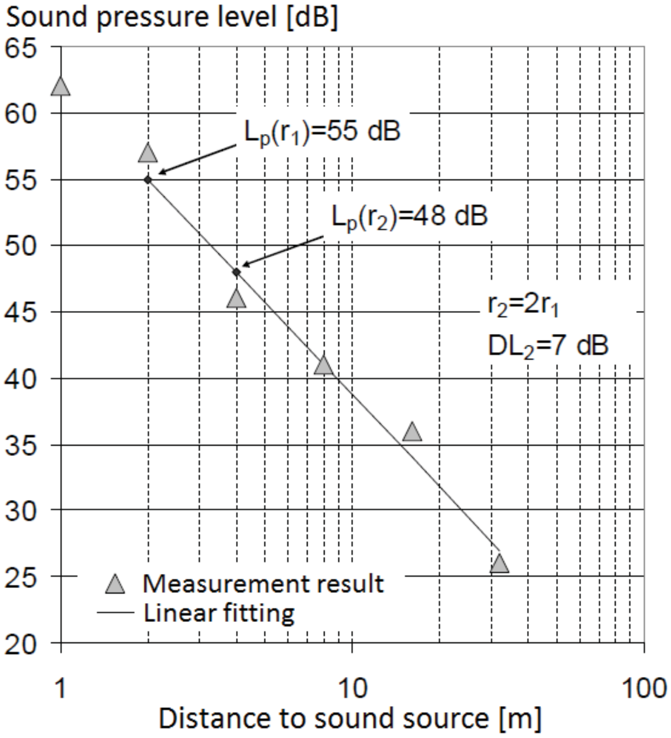


Figure 15: The definition of the rate of spatial decay per distance doubling, DL_2. Adopted from (Hongisto 2011).

In a free space (for example outdoors or in the anechoic chamber) $DL_2 = 6$ dB, thus it equals to free space attenuation. In more complex spaces (for example in open plan offices, classrooms, industrial halls) DL_2 is usually something else. Normally, the spatial sound distribution curve could be divided into two parts:

- Near region, where DL_2 is at most 6 dB and is usually smaller. The reasons to this are the reflections from the floor and the nearest furniture increasing the sound pressure levels. Near region covers usually the distance up to 4 meters or to the nearest obstacle affecting the propagation of sound.
- Far region, which is outside of the near region. In far region sound pressure levels could change strongly depending on the obstacles in the room, the amount of absorption and the position of the measurement point.

In normal rooms the values of DL_2 could be between 0 dB and 15 dB. DL_2 could also be predicted with room acoustical computer models or with regression equation models. The reliable modeling of the DL_2 requires that the absorption indices of the room surfaces are known. (ISO 3382-3:2012 2012; Hongisto 2011)

3.5 Strength (G)

Sound strength (G) is a room acoustical parameter, which describes the perceived "loudness" in the measured space (Hak et al. 2010). It is defined as the sound pressure level caused by an omnidirectional sound source on the stage, measured at a listener position in the hall, with reference to the sound pressure level at 10 m distance from the same sound source in a free field (ISO 3382-1:2009 2009). Basically strength is a similar parameter as normal sound pressure level, but with a different reference level (Beranek 2011). With stationary signal G is expressed as:

$$G = L_{p(listener)} - L_{p(dir,10m)} \text{ [dB]}, \tag{26}$$

where $L_{p(listener)}$ is the sound pressure level at a listener position and $L_{p(dir,10m)}$ is the sound pressure level measured at 10 m from the same sound source in a free field. $L_{p(dir,10m)}$ could be achieved by knowing the sound power level L_w of the source:

$$L_{p(dir,10m)} = L_w - 31 \text{ dB}. \tag{27}$$

Measuring the sound power level of the used sound source requires access to either a reverberation room or an anechoic room. This makes the measuring often more difficult, thus the value of G is possible to achieve with more convenient manner by using only measured impulse responses:

$$G = L_{pE(listener)} - L_{pE(dir,10m)} \text{ [dB]}, \tag{28}$$

where

$$L_{pE(listener)} = 10 \log \left(\frac{\int\limits_0^\infty p_{(listener)}{}^2(t)\ dt}{p_0^2} \right) \text{ [dB]}, \tag{29}$$

$$L_{pE(dir,10m)} = 10 \log \left(\frac{\int\limits_0^\infty p_{(dir,10m)}{}^2(t)\ dt}{p_0^2} \right) \text{ [dB]}, \tag{30}$$

where $L_{pE(listener)}$ is the sound exposure level of $p_{(listener)}$, $L_{pE(dir,10m)}$ is the sound exposure level of the $p_{(dir,10m)}$, $p_{(listener)}$ is the instantaneous sound pressure of the impulse response from the listener position, $p_{(dir,10m)}$ is the instantaneous sound pressure of the impulse response from 10 m distance in a free field, and $p_0 = 20\ \mu\text{Pa}$ (ISO 3382-1:2009 2009). Still, as $L_{pE(dir,10m)}$ could be difficult to measure it could be determined by measuring the impulse response in 1 m distance and scaling it appropriately:

$$L_{pE(dir,10m)} = L_{pE(dir,1m)} + 20\log\left(\frac{1}{10}\right) \text{ dB}, \tag{31}$$

where $L_{pE(dir,1m)}$ is the sound exposure level in 1 meter distance (ISO 3382-1:2009 2009). Now we can write:

$$G = 10\log\left(\frac{\int\limits_0^\infty {p_{(listener)}}^2(t)\ dt}{\int\limits_0^\infty {p_{(dir,1m)}}^2(t)}\right) + 20 \text{ dB}. \tag{32}$$

Usually G is expressed as an average of the mid-frequency octave bands (1000 Hz and 500 Hz) and is then written as G_{mid}. The change of G along the distance from the source illustrates the diffuseness of the sound field in the room.

The expected value of strength in ideal conditions is:

$$G_{exp} = 10\log\left(\frac{T}{V}\right) + 45 \text{ dB}, \tag{33}$$

where T is the reverberation time and V is the volume of the room (Rossing 2007).

3.6 Clarity (C_{50})

Clarity, i.e. early-to-late index, marked as C_{50} or C_{80}, is the ratio between early received sound energy (first 50 ms or 80 ms of the impulse response) and the rest of the sound energy (time after the 50 ms or 80 ms):

$$C_{t_e} = 10\log\frac{\int\limits_0^{t_e} p(t)^2\ dt}{\int\limits_{t_e}^{\infty} p(t)^2\ dt} \text{ [dB]}, \tag{34}$$

where $p(t)$ is the instantaneous sound pressure of the impulse response measured at the measurement point and t_e is the desired time window (50 ms or 80 ms) (ISO 3382-1:2009 2009). The 50 ms time value is considered to suite best for determining the speech's clarity and 80 ms value is more suitable for music. Because clarity is a ratio of early and late energy, high values of it indicate the presence of the direct sound and early reflections to be higher than the late reverberation. This corresponds to subjectively perceived clarity of the sound. Low values of clarity accordingly indicate an unclear and excessively reverberant sound. (Peltonen 2000)

Under ideal conditions the expected value of clarity could be calculated:

$$C_{exp} = 10\log\left(e^{(1.104/T)} - 1\right) \text{ [dB]}, \tag{35}$$

where T is the reverberation time (Rossing 2007).

3.7 Definition (D_{50})

Definition (D_{50} or D_{80}) is the ratio of early received sound energy (first 50 ms or 80 ms of the impulse response) and the total energy of the impulse response:

$$D_{t_e} = 10 \log \frac{\int\limits_0^{t_e} p(t)^2 \ dt}{\int\limits_0^{\infty} p(t)^2 \ dt}, \tag{36}$$

where $p(t)$ is the instantaneous sound pressure of the impulse response measured at the measurement point and t_e is the desired time window (50 ms or 80 ms) (ISO 3382-1:2009 2009). The 50 ms time value is considered to suite best for determining the definition of speech and 80 ms value is more suitable for music. Definition represents the distinctness, clarity and intelligibility of speech or music (Peltonen 2000). Definition is related to the clarity by the following equation (ISO 3382-1:2009 2009):

$$C_{t_e} = 10 \log \left(\frac{D_{t_e}}{1 - D_{t_e}} \right) \ [\mathrm{dB}], \tag{37}$$

and the largest difference between clarity and definition is that the definition is expressed as a percentage, whereas the clarity is expressed in dB.

Under ideal conditions the expected value of definition is (Peltonen 2000):

$$D_{exp} = 10 \log \left(e^{k t_e} \right). \tag{38}$$

3.8 Center time (T_s)

Center time (T_s) is the time of the center of gravity of the squared impulse response:

$$T_s = \frac{\int\limits_0^{\infty} t \ p(t)^2 \ dt}{\int\limits_0^{\infty} p(t)^2 \ dt} \ [\mathrm{s}], \tag{39}$$

where t is the time instant and $p(t)$ is the instantaneous sound pressure of the impulse response. Center time avoids the discrete division of the impulse response into early and late energy parts (ISO 3382-1:2009 2009). A low value of center time indicates that most of the sound energy arrives early and high value corresponds to situation where energy arrives late after the direct sound. Low values of T_s indicate sound to be clear, while high values indicate a reverberant sound. (Rossing 2007; Peltonen 2000)

In diffuse conditions the expected value of the center time is:

$$T_{s,exp} = \frac{T}{13.8} \ [\mathrm{s}], \tag{40}$$

where T is the reverberation time (Rossing 2007).

4 Acoustics of public spaces

This chapter consists of review of the acoustic classification of buildings and descriptions of typical sound environments, acoustical requirements and recommendations of classroom, healthcare space, and open plan office. Also, solutions for enhancing the sound environments of the before mentioned spaces are provided.

4.1 General sound environment and requirements

In Finnish standard SFS 5907: *Acoustic classification of spaces in buildings* different building types have been divided into four classes, A, B, C, and D, based on their acoustical condition. Class A is the most demanding to achieve and class D is the lightest class. Class C corresponds to the minimum requirements of new buildings for those parts which are defined in Finnish building regulations, part C1-1998. In room acoustics class C corresponds to the typical acoustical conditions in buildings. Class D represents acoustical conditions of old buildings containing less satisfactory sound environment. The classification includes determination of airborne sound insulation, step sound insulation, the reverberation time, and speech transmission index values. The recommendations in following sections are values of acoustical class A or B. (SFS 5907:2006 2006)

Buildings and spaces could also be divided into three indoor air classes, S1, S2, and S3, according to indoor air classification of Finnish Indoor Air Association. Class S3 corresponds to Finnish land use and building law and health protection law. Class S1 is the most satisfactory class. Indoor air classification includes desired values for temperature, air quality, lighting, and acoustics. (Indoor Air Association 2008)

4.1.1 Classroom

A classroom in this context refers to an elementary or an upper comprehensive school classroom. These kinds of classrooms are usually arranged in the way that the teacher is mainly talking in the front of the class and pupils are sitting either in rows or in small groups.

The starting point for an acoustical design in classrooms is a demand for a good speech intelligibility and a low background noise. Noise levels has been shown to correlate with the reverberation time, thus decreasing the reverberation time is also desirable (Canning and James 2012). Noise has been shown to be the most distracting factor concerning the speech intelligibility in classrooms (Smirnowa and Ossowski 2005; Kristiansen et al. 2011; Björkholts 1988). Attenuation of noise and improvement of the speech intelligibility sets a contradiction for the acoustical treatment of the room. To attenuate noise an adequate amount of absorbing material should be used. However, if too large amount of absorbing material is installed the speech transmission index will start to decrease especially in the rear parts of the room due to decreasing speech level (Nilsson 2010; Smirnowa and Ossowski 2005).

Standard SFS 5907 (SFS 5907:2006 2006) sets target values for the speech transmission index and for the reverberation time in classrooms, which are 0.80 and 0.50

- 0.60 s correspondingly. To achieve these targets at least 30% of the maximum area of ceiling and walls should be covered with absorbing material, which is preferably installed on the ceiling and on the back wall of the room (Figure 16) (Smirnowa and Ossowski 2005). However, Canning and James suggest as short reverberation time as possible in all octave bands (Canning and James 2012) and that requires basically at least the whole ceiling to be covered with acoustic panels. In addition, to have good STI-values throughout the classroom, the middle part of the ceiling could be covered with more reflective material to allow reflections from the teacher to the rear part of the room, especially in larger rooms (length > 8 m) (Hirvonen 2007b). Low frequency absorbers has also shown to enhance the learning environment by improving the low frequency clarity. For example, the fundamental frequency of a male's voice is normally slightly over 100 Hz and normal acoustic panels absorb rather poorly in that frequency region. (Canning and James 2012) The low frequency treatment could be realized with thick low frequency absorbing panels placed above the normal acoustic ceiling around the edges of the room (Figure 16) or with different kinds of bass traps (see Section 2.1.3).

Teacher's speaking conditions should also be taken into account. To offer a support to the voice of the teacher, a reflecting surface should be placed above the teacher (fig. 16) (Sala and Viljanen 1995). Also, when the value of strength parameter of the room is high enough, the room amplifies the speech of the teacher (Brunskog et al. 2009).

To determine acoustical conditions of the classroom the reverberation time, strength, clarity, speech transmission index, and background noise level should be measured.

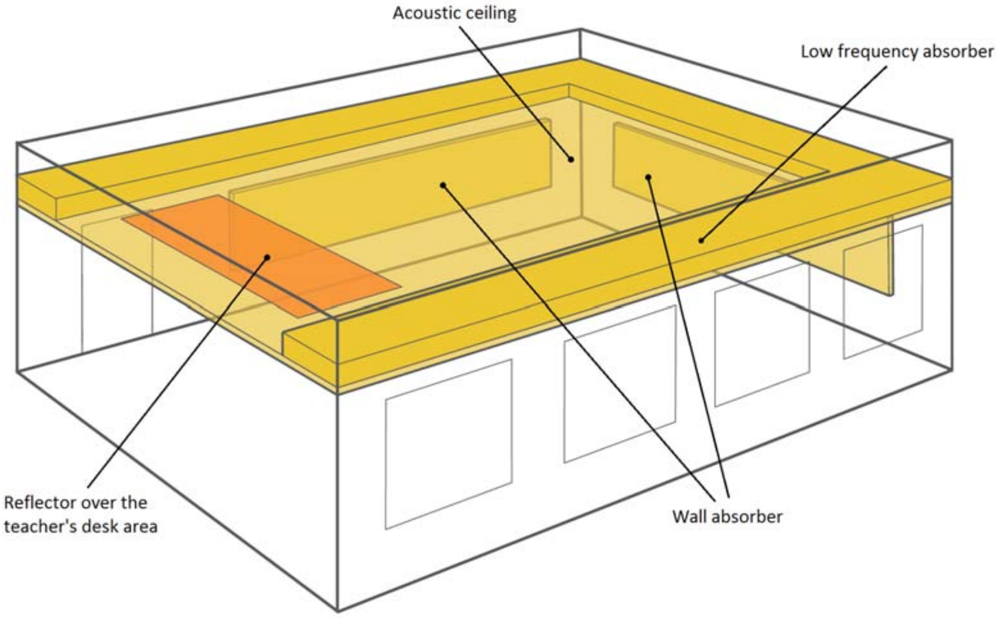


Figure 16: Optimal acoustical treatment of a classroom. Adopted from (Ecophon Saint-Gobain 2006).

4.1.2 Healthcare space

A good sound environment in hospital wards is undeniably important. Excessive noise could affect negatively to the quality of sleep and the overall health of patients and the stress level of the personnel (Salandin et al. 2011; Busch-Vishniac et al. 2005; MacLeod et al. 2007; Hagerman et al. 2005). The lack of privacy could be also a problem. One of the most important matters concerning patient rooms is to offer enough tranquillity and privacy to the healing patients. In addition, the speech intelligibility is important as most of the data and knowledge transmission between people in hospitals is performed orally (MacLeod et al. 2007).

In healthcare spaces exists a large amount of different noise sources. The most typical noise sources are personnel tasks, operating noise of the devices, portable carts, HPAC, and different device alarms (Salandin et al. 2011). Background noise level depends also on the type of the space. For example in restrooms the background noise level is generally lower than in intensive care units.

Hospital environment requirements set challenges to the acoustical treatment. The acoustic materials installed in the healthcare space should be durable, cleanable, fire safe, in many cases moisture resistant, have a low particle emission, and have a high absorption rate. These are usually the reasons why ceilings and walls in hospitals are hard.

World Health Organization (WHO) recommends the maximum equivalent background noise level to be $L_{eqmax} = 30$ dB in patient's sickrooms and as low as possible in medical treatment rooms (WHO 1999). Finnish standard SFS 5907:2006 recommends corresponding values to be $L_{eqmax} = 29$ dB in patient's rooms and $L_{eqmax} = 38$ dB in treatment rooms (SFS 5907:2006 2006). Recommendations for reverberation times are $T_{60} = 0.6$ s in patient's rooms and $T_{60} = 0.4$ s in resting or treatment rooms (SFS 5907:2006 2006). It is quite general that background noise levels in hospital wards exceed the recommendations of WHO (Ryherd et al. 2008; Salandin et al. 2011; Busch-Vishniac et al. 2005).

To determine the acoustical conditions in healthcare spaces at least the reverberation time, strength, clarity, and speech transmission index should be measured.

4.1.3 Open plan office

Open plan office is an office which contains multiple workstations separated only with screens or with nothing. The lack of actual walls between individual workstations sets certain problems in acoustics. The occupants are all the time affected by activities surrounding them. Poor acoustic conditions can cause distraction, loss of concentration, and a lack of speech privacy.

Noise has shown to be the largest problem in open plan offices and the most distracting individual noise factor is speech. Especially in cognitively demanding tasks other people's speech could be very disturbing. The loudness of the speech is not considered as harmful as the distinctness of the speech. This is the reason why the acoustical planning of open plan offices generally aims to low values of STI and high values of DL_2. A certain contradiction still exists, because STI between occupants working together should be high, whereas STI between the occupant and the rest office should be low. (Haapakangas et al. 2008; Keränen et al. 2008; ISO 3382-3:2012 2012)

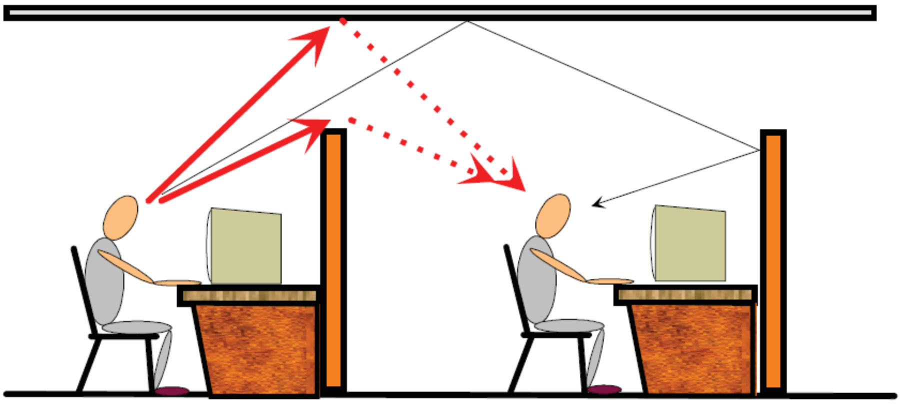


Figure 17: Different ways where the sound propagates from a workstation to another in an open plan office. (Chu and Warnock 2002)

A solution to decent acoustical conditions in open plan offices is sound absorbing acoustic ceiling, sound absorbing walls, high enough sound absorbing screens between the workstations, and in some cases the use of a masking sound in an appropriate level could be considered. Screens between individual workstations should be sound absorbing and at least 170 cm high when performing cognitively demanding tasks (Keränen et al. 2012). The ceiling and the screen absorptions are also important because the sound propagates from workstation to another over the screens by diffracting and by reflecting from the ceiling (Figure 17).

The masking sound could be either natural (for example HPAC-system's sound) or artificial (masking sound system). HPAC-system's sound pressure level is usually too low in Finnish offices because Finnish building regulations recommends sound pressure level for HPAC-systems in offices to be only 33 dB (Hirvonen 2008). The masking sound system consists of a large number of loudspeakers installed on the ceiling and a central unit producing the sound. The sound pressure level of the masking sound should normally be 40 dB - 45 dB and its spectrum should correspond to the normal speech spectrum (Figure 18) (Hirvonen 2008). An appropriate masking sound reduces the value of STI significantly, thus it improves the speech privacy (Keränen et al. 2008).

According to the new open plan office standard ISO 3382-3:2012: *Acoustics - Measurement of room acoustic parameters - Part 3: Open plan offices*, to determine the acoustical conditions of a certain office at least STI, DL_2, and r_d (see Section 3) should be measured. The reverberation time should also be measured but it is questionable whether it provides any relevant information in the case of open plan office. Example target values to measured quantities for good conditions are $DL_2 \geq 7$ dB and $r_d \leq 5$ m according to ISO 3382-3:2012.

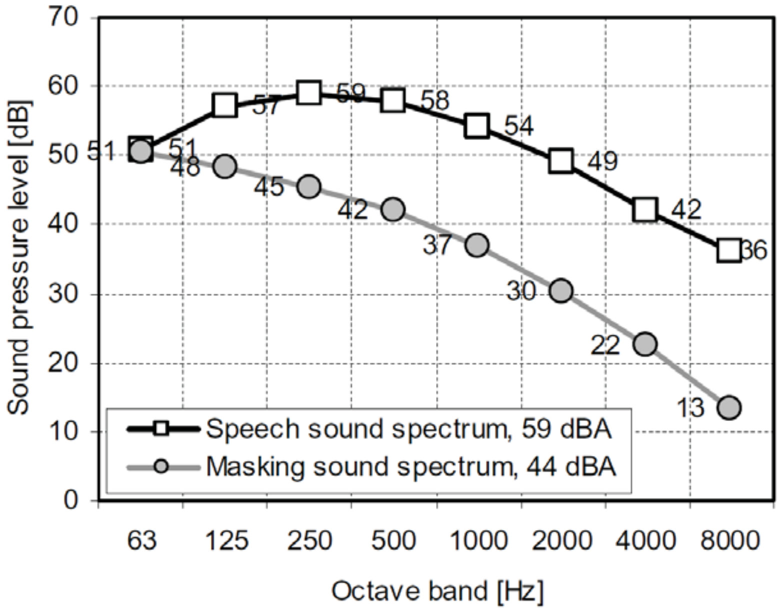


Figure 18: The spectrum of speech sound (1 m from the source) and the masking sound spectrum. (Keränen et al. 2008)

4.2 Acoustical solutions

Acoustics of a room could be improved by using different kinds of absorbing materials. The most common way of using absorbing materials is acoustic ceiling consisting of acoustic panels. Wall- and other absorbers could also be used to further improve the room absorption.

Acoustic materials could be divided into five absorption classes, A, B, C, D, and E, according to standard EN 11654: *Sound-absorbing materials for use in buildings - Evaluation of acoustic absorption*. Class A represents the highest absorption and class E the lowest. The requirements of absorption classes are presented in Figure 19. (Hirvonen 2007a)

4.2.1 Acoustic panels and resonators

To adjust the acoustic conditions in a room different kinds of acoustic panels or resonators could be used. Different solutions are manufactured either from fibrous-, perforated-, or solid panel-type material. Special low frequency absorbers, called bass traps, could be based on any of foregoing absorber types.

Fibrous absorbers

Fibrous absorbers are normally made of high absorptive porous materials, such as mineral wool which includes glass wool, rock wool, and slag wool. The principles of sound absorption are presented in Section 2.1.3. Generally, fibrous absorptive panels absorb higher frequencies better than lower. Lower frequencies require thicker panel. Thicker panels absorb all frequencies better, because the sound wave has a longer

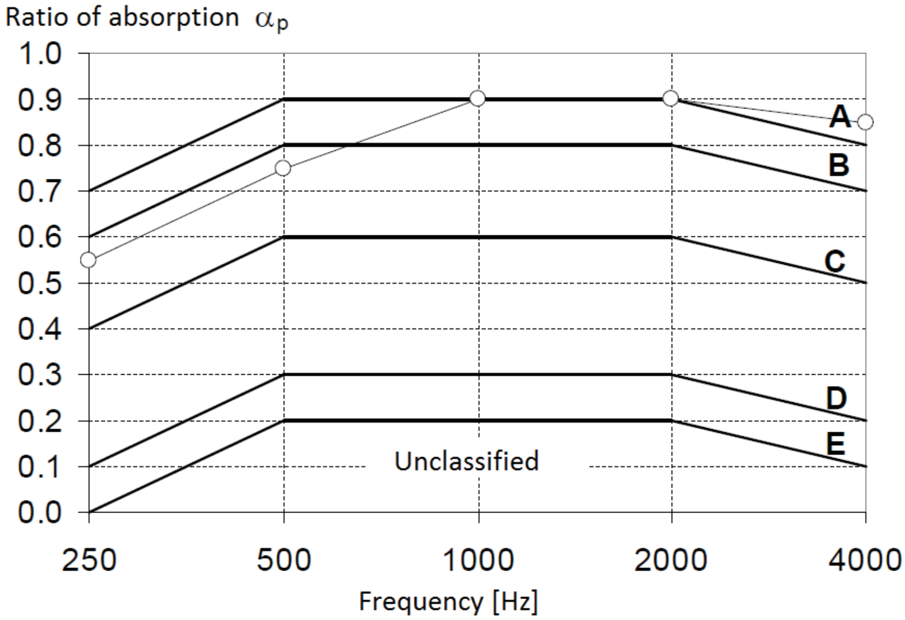


Figure 19: EN 11654 classification for absorption materials. The example material (marked with circles) achieves class B, because the sum of the deviations of the measurement results under the reference curve is smaller than 0.10. Adopted from (Hongisto 2011).

path to travel inside the material. Acoustic panels made of fibrous materials are often covered with some acoustically transparent material, such as thin fabric, to achieve more aesthetic appearance and to prevent particle emission. (Rossing et al. 2002)

Acoustic panels could be mounted directly on the ceiling or on the wall. Other possibility is to build suspended ceiling where an air space is left between the panels and the reflecting surface behind. The particle velocity of the sound wave is zero at the reflecting surface, thus moving the panel away from the surface allows the particle velocity and thus the absorption to be greater. Suspended ceiling improves the absorption especially at lower frequencies and the same method could also be used when mounting panels to the walls. (Rossing et al. 2002; Rossing 2007)

Perforated absorbers

In addition to fibrous panels, perforated panels such as perforated gypsum or metal boards are used. The small holes in the panel form small Helmholtz resonators, which absorb the sound at their resonance frequency. The frequency range of effective absorption could be altered by changing the thickness of the panel, the thickness of the air gap behind the panel, and the size and placement of the holes in the panel. Perforated absorbers could also be backed with fibrous material to improve the total absorption and they are installed in the same manner as the fibrous panels. (Rossing et al. 2002)

Panel absorbers

Panel absorber consists of a cavity sealed with a thin rigid panel or diaphragm and possible absorbing material inside the cavity. The thin panel starts to vibrate and resonate along the sound wave and using the sound energy in internal friction. This kind of absorber operated best at lower frequencies. The frequency range of the panel absorber could be tuned with the panel mass and with the size of the cavity. The possible absorbing material inside the cavity enhances the absorption of the absorber. The difference between the panel absorber and the perforated panel absorber is illustrated in Figure 20. (Rossing et al. 2002)

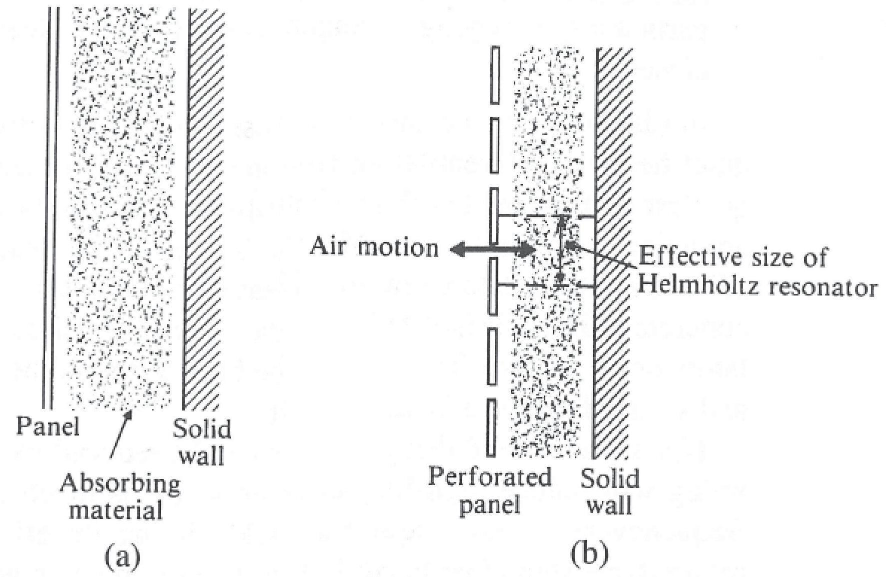


Figure 20: (a) Panel absorber placed away from a reflecting wall. (b) Perforated panel absorber backed by porous material. (Rossing et al. 2002)

Bass traps

Low frequency absorbers, so called bass traps, could be either Helmholtz resonators, cavity resonators as panel absorbers or absorption panels made of rigid and thick glass wool or similar porous material. Helmholtz resonators work in a fairly narrow frequency band, whereas panel absorbers filled with absorption material, like glass wool, operate in a wider range. Bass traps based on thick porous material have the widest frequency range and the absorption could be improved using a membrane with the porous material. Bass traps are usually used to treat the room in the frequencies below 300 Hz and they are normally placed in the corners of the room where all the room modes have their maximum, thus improving the absorption. (Winer 2004; Rossing et al. 2002)

4.2.2 Other solutions

Some acoustical treatment could be realized also with other elements than actual absorption panels or absorbers. Curtains are for example very common in normal rooms regardless of the purpose of the room. Normal curtains are too light to have a noticeable absorption, thus to achieve a better absorption thicker and heavier curtains should be used. Folded cotton curtain, which has a mass of 330 g/m^2, absorbs mainly higher frequencies starting from about 1 kHz. However, the rate of absorption is over 0.8 after 2 kHz (Hongisto 2011).

Carpet could also be used to increase the overall absorption in rooms. Carpets absorb sound energy mainly in higher frequencies starting from about 1 kHz. Unlike the curtains, the rate of absorption of carpet stays under the value of 0.5 in all frequencies (Hongisto 2011). In addition, carpets attenuate the noise resulting from furniture movements and walking.

Diffusers are used mainly in listening rooms or in home theatres to provide a more diffuse sound field in the room. Diffusers can help to reduce flutter echoes. The working principle of diffusers is explained in Section 2.1.2.

All normal furniture and people in the room also absorb sound energy. For example in chairs the thicker the upholstering they contain the greater the absorption is. Beds and soft couches work also as absorbers.

5 Measurement methods and measured spaces

This chapter consists of a description of used measurement devices and software. The used measurement techniques are also explained. In addition, the measured spaces, classroom, healthcare space, and open plan office, are described. Floor plans, measurement positions, and descriptions of spaces' acoustical conditions before and after the acoustical treatment are provided.

5.1 Devices and programs

Measurements were carried out using an integrated impulse response method using logarithmic sine-sweep as a stimulus. Measurement setup in healthcare spaces and in classroom consisted of Lenovo X200 laptop containing Room Eq Wizard 5.0 -room measurement program, Genelec 8030A active loudspeaker (Figure 21) and Norsonic Nor140 precision sound measurement device (Figure 21), which contained Nor1209 pre-amplifier and Nor1225 microphone capsule. In open plan office measurements were carried out with otherwise the same equipment but the loudspeaker was omnidirectional Norsonic Nor270 (Figure 22) and Norsonic Power Amplifier Nor280 (Figure 22) was also used. Norsonic sound level measurement device was used as a microphone in impulse response measurements and it was calibrated before each measurement with class 1 Norsonic Nor1251 calibrator (Figure 21). Laptop contained Conexant 20561 SmartAudio HD soundcard, which influence to measurements was minimized by calibrating the measurement software with the soundcard's frequency response. STIPA and all sound pressure levels were measured directly with Norsonic Nor140 sound level meter. Reverberation times were calculated from measured impulse responses by Room Eq Wizard and strength values were calculated from measured impulse responses with Microsoft Excel. Spatial decay rates were also calculated with Microsoft Excel.

5.2 Measurement techniques

Impulse responses of the rooms in healthcare spaces and in classroom were measured placing the sound source on the floor to the corner of the room the way that the emitted sound spreads throughout the room by reflecting from the corner. In open plan office the omnidirectional sound source was placed 120 cm above the floor to the place of the workers head. Impulse responses were measured in 4 to 8 different positions in the room with the microphone and then averaged to obtain a spatial average of the room's impulse response. Two measurements were conducted and averaged in each measurement position. The total reverberation time (T_{60}), reverberation times in octave bands (T_{60_i}), strength (G), and clarity (C_{50}) were calculated from the obtained impulse response. In impulse response measurements the minimum distance between the source and the microphone is:

$$d_{min} = 2\sqrt{\frac{V}{cT}}, \tag{41}$$

Figure 21: Measurement devices for the healthcare space and for the classroom. From left: class 1 calibrator Norsonic Nor 1251, sound level meter Norsonic Nor140, and loudspeaker Genelec 8030A.

where V is the volume of the room, c is the speed of sound and T is an estimation of the expected reverberation time (ISO 3382-2:2008 2008).

STIPA was measured by placing the sound source to the place of a possible talker in the room, playing the STIPA excitation signal trough it and measuring the STIPA value in the place of the possible listener with Norsonic measurement device. Three measurements were conducted and averaged in each measurement position to obtain a reliable value.

Rate of spatial decay of sound pressure level per distance doubling (DL_2) was

Figure 22: Measurement devices for the open plan office. From left: Lenovo X200 laptop, sound level meter Norsonic Nor140, Norsonic Power Amplifier Nor280, and omnidirectional loudspeaker Norsonic Nor270.

measured by placing the sound source to the place of a possible talker in the room, playing pink noise through it and measuring the A-weighted equivalent sound pressure levels in different distances from the source. Ten second integration time was used and at least two measurements were made and averaged in each measurement position. Background noise levels were measured in the same manner as DL_2 measurements.

5.3 Measured spaces

5.3.1 Classroom

Measured classroom was a small ordinary rectangular classroom in the Piikkiö comprehensive school. The floor plan of the room is illustrated in Figure 23.

Before the acoustical treatment the room contained a large blackboard (4.00 m × 1.23 m) on the back wall, a noticeboard (3.00 m × 1.23 m) on the side wall, large windows (4.52 m × 1.35 m) on the other side wall, an air conditioning device (2.10 m × 1.10 m × 0.77 m, metallic cover), and a sink. All the walls were made of concrete. On the floor was wall-to-wall plastic mat. The classroom contained suspended ceiling consisting of class D perforated gypsum panels (Gyptone BIG Quattro 47, 12 mm × 12 mm rectangular perforation, perforating percent 6%, absorption ratios presented in Figure 24) covering 64% of the ceiling area, while the remaining 36% was covered with solid gypsum board. The overall depth of the suspended ceiling (from the lower surface of ceiling to the lower surface of panel) was 100 mm and on the top of the panels was thin acoustical felt. The classroom was measured when it was empty and when it was furnished with normal classroom furniture. Pictures of the measured classroom before the treatment are illustrated in Appendix A.

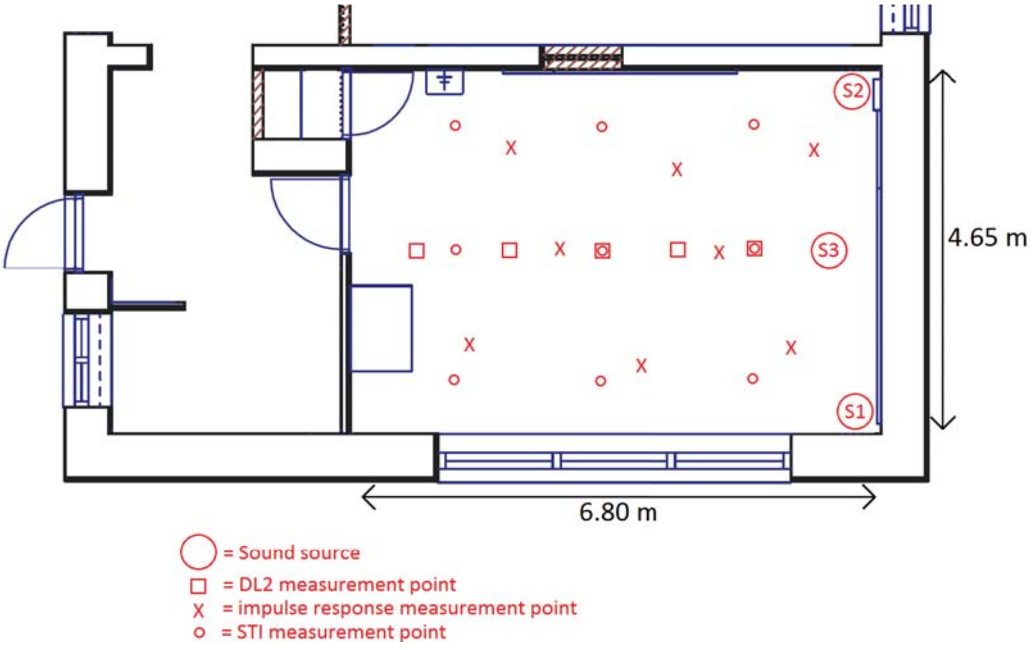


Figure 23: Measured classroom floor plan and measurement positions.

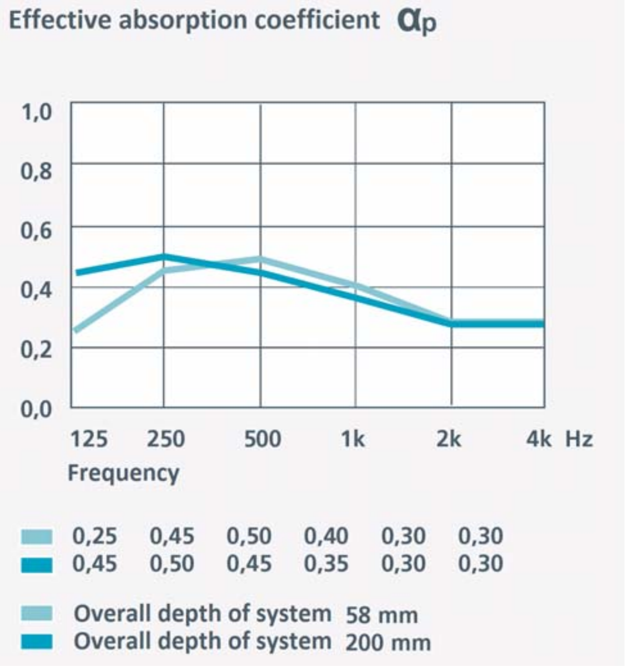


Figure 24: Absorption indices in octave bands of the Gyptone BIG Quattro 47 -perforated gypsum panel (www.gyptone.fi).

After the treatment the room was measured with two different acoustical solutions. In the first condition the classroom was identical to the before condition, except it contained suspended ceiling consisting of class A absorbing glass wool panels (Ecophon Master Rigid Dp, absorption ratios presented in Figure 25) covering 95% of the ceiling area and additional bass absorbers (Ecophon Extra Bass, absorption ratios presented also in Figure 25) placed above the suspended ceiling encircling the room at the edges of the ceiling (covering 120 cm wide area from the walls). Above the teacher position was no additional bass absorbers. The ceiling was installed below the former perforated gypsum -ceiling and the overall depth of the new suspension was 10.5 cm. The second condition was identical to the first condition, except that the noticeboard on the side wall was replaced with 420 cm × 135 cm class A absorbing wall panel (Ecophon Wall Panel C, absorption ratios presented in Figure 26). Again room was measured when it was empty and when it was furnished. Pictures of the measured classroom after the treatment are also presented in Appendix A.

The reverberation time, rate of spatial decay of sound pressure level per distance doubling, strength, clarity, and speech transmission index were measured. Source- and measurement positions are illustrated in the Figure 23. In the reverberation time, strength, and clarity measurements the source (S1 and S2 in the Figure 23) was placed on the floor in the corner of the room facing towards the corner. The reverberation time, strength, and clarity were measured in all eight points marked with X in the Figure 23 with two source positions (S1 and S2) and then averaged. Two consecutive measurements were taken in each measurement point and averaged.

In DL_2 and STI measurements the source (S3 in the Figure 23) was placed 120 cm above the floor on the supposed position of the teacher. DL_2 was determined measuring sound pressure levels in different distances from source towards the door (marked with squares in Figure 23). Two measurements were averaged in each position. STI-values were measured in six positions around the classroom (marked with small circles in Figure 23). Three measurements were averaged in each position.

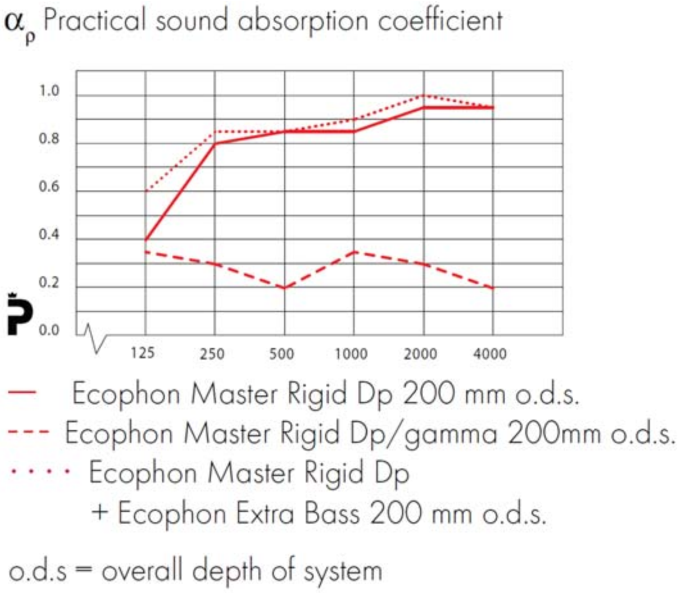


Figure 25: Absorption indices in octave bands of the Ecophon Master Rigid Dp glass wool panel and additional Ecophon Extra Bass bass absorber (www.ecophon.fi).

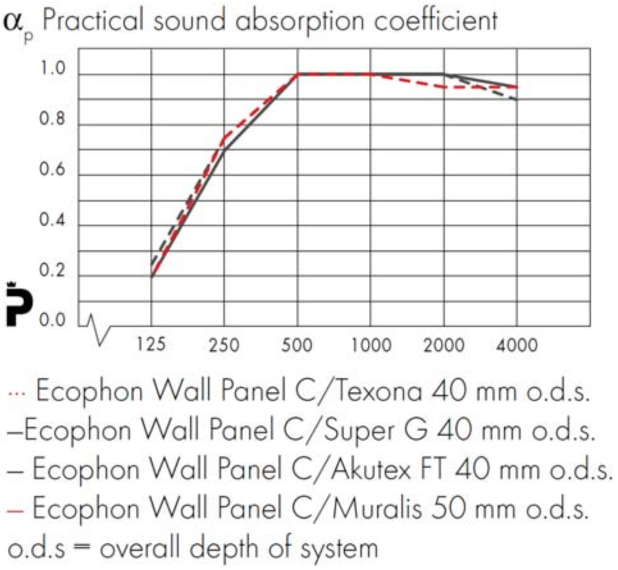


Figure 26: Absorption indices in octave bands of the Ecophon Wall Panel (www.ecophon.fi).

5.3.2 Healthcare space

Measured healthcare space was small two-person patient room in the joint-stock property company Kiinteistö Oy Seinäjoki's new Y-building in Seinäjoki. Actually, two geometrically completely identical (with the exception of they were mirror images from each other) rooms were measured. The floor plans of the measured spaces are illustrated in Figure 27. The room number 1 contained suspended ceiling consisting of class A absorbing panels (Ecophon Focus A, absorption ratios presented in Figure 28) covering 85% of the ceiling area, and the room number 2 contained suspended ceiling consisting of class C perforated gypsum panels (Knauf Plaza G1, 6 mm circular perforation, perforating percent 10.2%, absorption ratios presented in Figure 29) covering the same area as in the room number 1. The air space above the acoustical panels was 60 cm. The room number 2 contained large window on the opposite wall of the door, whereas the room number 1 contained only a small ventilation window on the corresponding wall. The rooms contained only fixtures including three cupboards, two small shelves, a sink, and a drawer. The ceiling material was only high absorbing material in the rooms. Pictures of the measured rooms are presented in Appendix B.

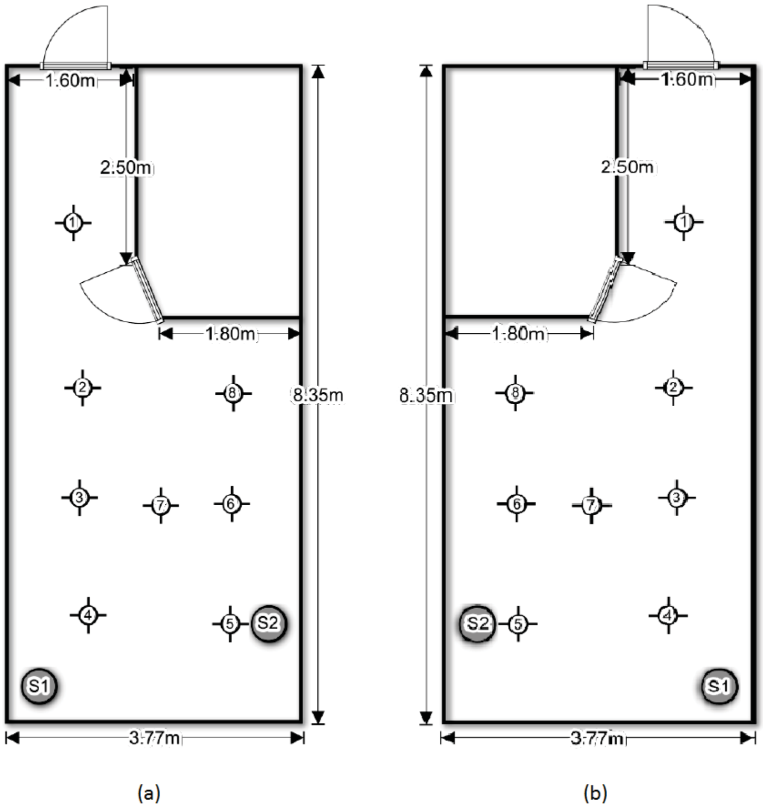


Figure 27: Measured patient rooms. Positions of the sound sources are marked with S1 and S2. Microphone positions are marked with numbers 1-8. (a) The room with the class A glass wool absorbing panels. (b) The room with the class C perforated gypsum panels.

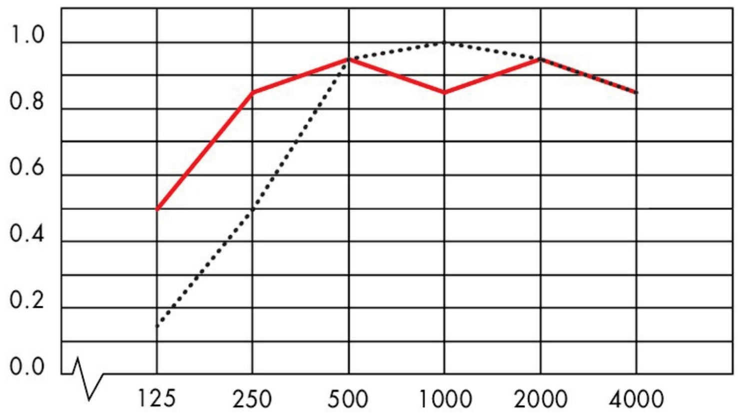


Figure 28: Absorption indices of Ecophon Focus A panel in octave bands (www.ecophon.fi). Red line: Overall depth of system (from the lower surface of ceiling to the lower surface of panel): 200 mm, dashed line: Overall depth of system: 50 mm.

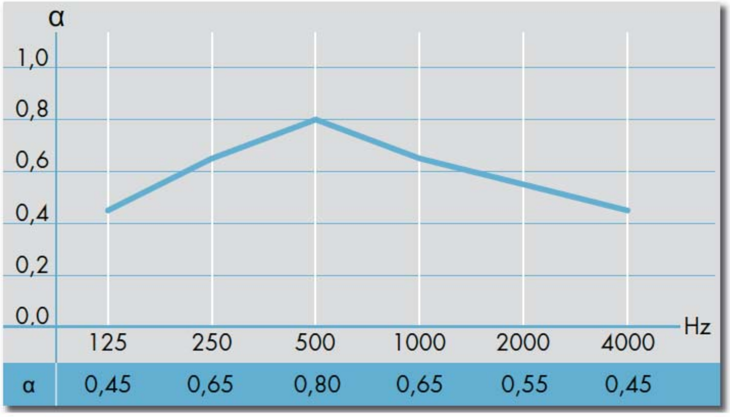


Figure 29: Absorption indices of Knauf Plaza G1 panel in octave bands (www.knauf.fi). Measurements are made with 200 mm overall depth of system (from the lower surface of ceiling to the lower surface of panel) and no additional mineral wool installed.

The reverberation time, clarity, and speech transmission index in several positions were measured. Source- and measurement positions are illustrated in Figure 27. In the reverberation time and the clarity measurements the source (S1 in the Figure 27) was placed on the floor in the corner of the room facing towards the corner. The reverberation time, strength, and clarity were measured in all eight points marked in the Figure 27 and then averaged. Two consecutive measurements were taken in each point and averaged. Speech transmission index was measured in points 1, 4, and 6 when the source was placed 50 cm from the wall and 90 cm above the floor (S2 in the Figure 27). Three measurements were averaged in each measurement position. Source was in the place of the hypothetical laying patient's head. Measurement point 4 represents a sitting person near the foot of the bed, point 6 represents the other laying patient's head and point 1 represents a person entered the room.

5.3.3 Open plan office

Measured open plan office was part of the bureau of the Finnish Real Estate Federation (Suomen Kiinteistöliitto) in Helsinki. The measured space contained four open plan office rooms which all open up to the same corridor. The corridor ceiling was suspended ceiling containing 25 mm mineral wool panels covering 50% of the ceiling area. The floor plan of the measured space is illustrated in Figure 30. All rooms were 355 cm high and the corridor was 252 cm high. Three of the rooms were two-person rooms and one of the rooms was four-person room. Between the workstations in two-person rooms were 170 cm high screens and in four-person room the screens were 200 cm high forming small booths for employees. Between the rooms were roughcasted brick walls (containing unused doors between the room 336 and the room below and between rooms 338 and 339, and rooms 338 and 336, see Figure 30). The corridor wall was made of concrete and the floor was parquet in every room and in the corridor. Pictures of the office before and after the treatment are presented in Appendix C.

Before the acoustical treatment the office contained the above mentioned corridor ceiling, class C absorbing screens, and 2-5 mm thick Decocoat acoustic spray coating covering 55% of the ceiling area. Above the spray coating was also 20 mm thick mineral wool panels and then 20 mm air space, thus the total absorption class of the ceiling material is B. Absorption indices of Decocoat acoustic spray coating are presented in Figure 31.

After the acoustical treatment the office contained all above mentioned acoustical solutions and additional class A Ecophon Wall Panel C -panels assembled to the walls of office rooms and corridor. In rooms the panels were attached on the wall from desk level to the corner of the ceiling and wall. Practically all free wall surfaces were covered with wall panels. In the corridor on the unbroken wall (left wall in the Figure 30) was installed 480 cm × 135 cm absorptive wall panel. Absorption indices of Ecophon wall panel are presented in Figure 32.

The reverberation time, speech transmission index, rate of spatial decay of sound pressure level per distance doubling, strength, and clarity were measured. The reverberation time, strength, and clarity were measured only in room 338. Omnidirectional sound source was placed into room 338 or room 336 to the place of the office worker's head 120 cm above the floor. Source and measurement positions are illustrated in Figure 30. The reverberation time, strength, and clarity were measured in four positions marked with X in Figure 30 and averaged. Two consecutive measurements were made in each position and averaged. Speech transmission index was measured in all numbered positions as well as DL_2. In STI and DL_2 measurements three measurements were averaged in each position.

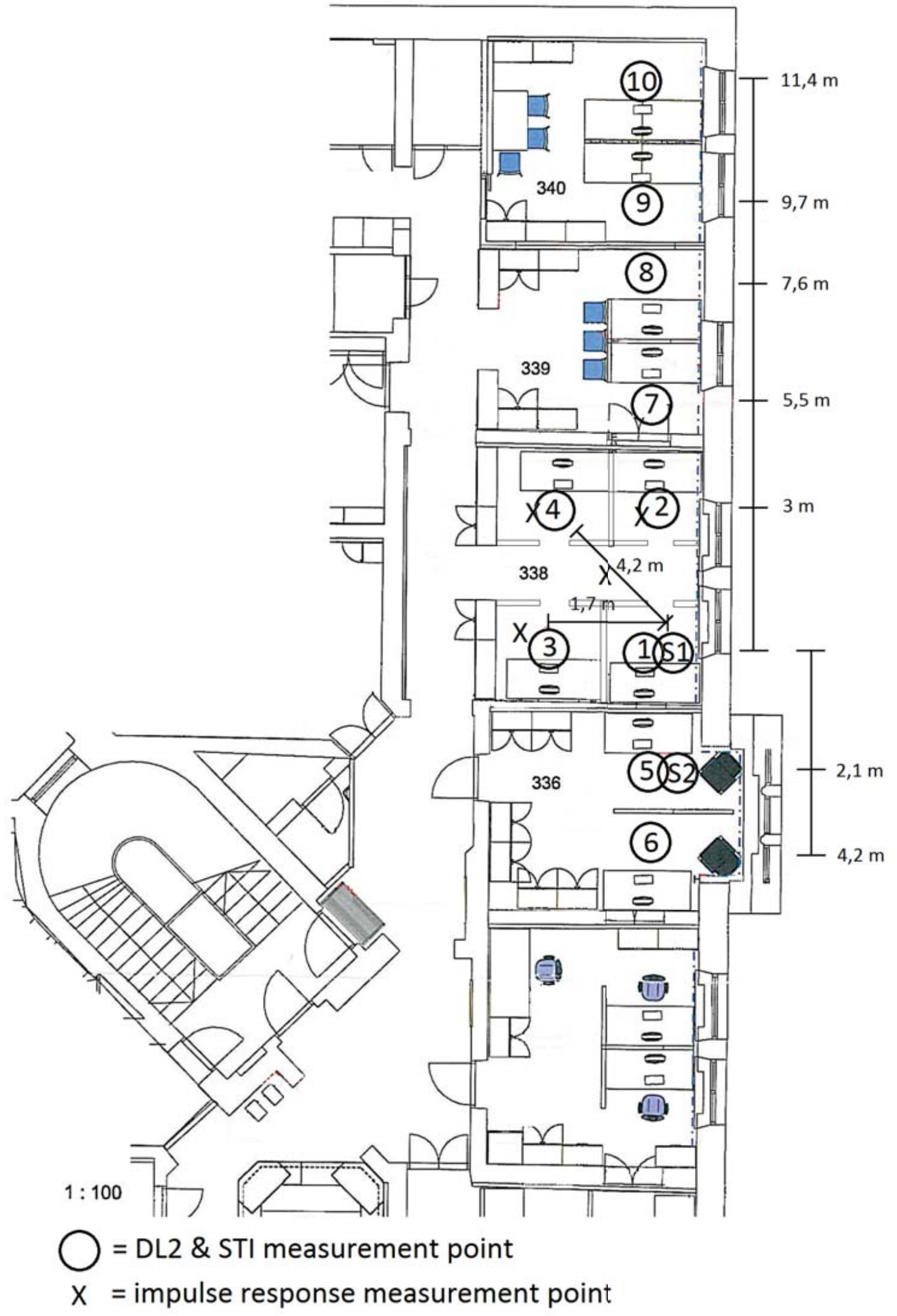


Figure 30: Measured open plan office. Numbered rooms (336, 338, 339, 340) were measured.

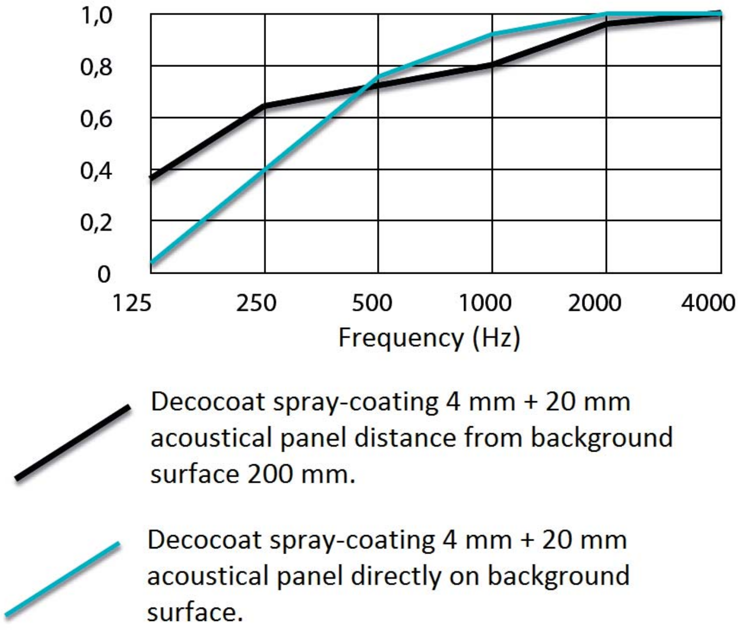


Figure 31: Absorption indices of Decocoat acoustic spray coating in octave bands (www.decocoat.fi).

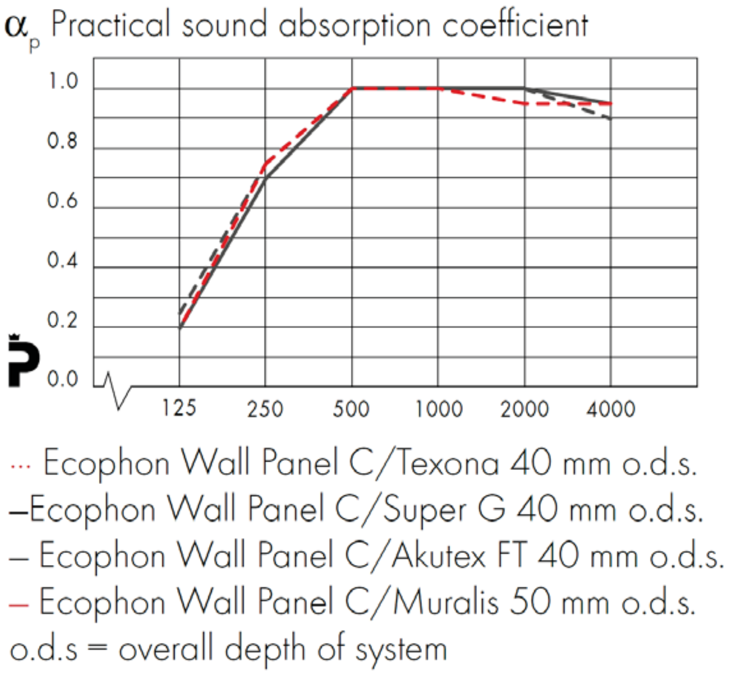


Figure 32: Absorption indices of Ecophon Wall Panel in octave bands (www.ecophon.fi).

6 Results and analysis

Measurement results and their analysis are reported in this chapter. Measured results are compared to existing recommendations. Also, discussion and suggestions of possible improvements for acoustics of the measured spaces are presented.

6.1 Classroom

Reverberation times (T_{60}), A-weighted background noise levels (L_{bgA}), DL_2-values, strength values (G), and clarity values (C_{50}) of the furnished and the empty classroom before and after (with and without the absorbing wall panel) the acoustical treatment are presented in the Table 3. Reverberation times in octave bands of corresponding situations are presented in Figure 33. STI-values of empty and furnished classroom before and after (with and without the wall panel) acoustical treatment are presented in Figures 35a, 35b, and 35c correspondingly. Also, STI-values as a function of the distance are presented in the Figure 36. Expected reverberation times of the empty classroom calculated with Sabine's formula (18) are presented in Figure 34. The calculation of reverberation times is presented in Appendix A.

Table 3: Reverberation times (T_{60}), A-weighted background noise levels (L_{bgA}), DL_2-values, strength values (G), and clarity values (C_{50}) of the furnished and empty classroom before and after (with (w.p.) and without (no w.p.) the wall panel) the acoustical treatment.

	Empty room			**Furnished room**		
	before	**after**		**before**	**after**	
		no w.p.	**w.p.**		**no w.p.**	**w.p.**
$\mathbf{T_{60}}$ **(s)**	0.9	0.57	0.47	0.75	0.45	0.38
$\mathbf{L_{bgA}}$ **(dB)**	39.6	35.1	34.8	39.6	35.0	34.8
$\mathbf{DL_2}$ **(dB)**	1.2	1.4	2.9	1.3	3.6	4.0
G (dB)	15.0	11.5	12.1	12.8	12.8	15.4
$\mathbf{C_{50}}$ **(dB)**	3.8	9.9	10.4	4.3	9.2	11.0

Reverberation times in octave bands have decreased significantly after the acoustical treatment even without the wall panel (Figure 33). With the ceiling treatment and the wall panel the difference is over 0.4 s. The difference between the case without the wall panel and the case with the wall panel is about 0.1 s in mid and high frequency regions. In lower frequency region the values of the reverberation time are nearly the same with or without the wall panel. This is due to the poor absorbing ability of the wall panel in lower frequencies (see Figure 26 in Appendix A). From the Figure 33 could be seen that after the treatment the reverberation times in lower frequency region have decreased to the same level or below the mid and high frequency values. The reason to this is the used additional bass absorbers above the ceiling. Without the bass absorbers the ceiling's ability to absorb low frequencies would be weaker.

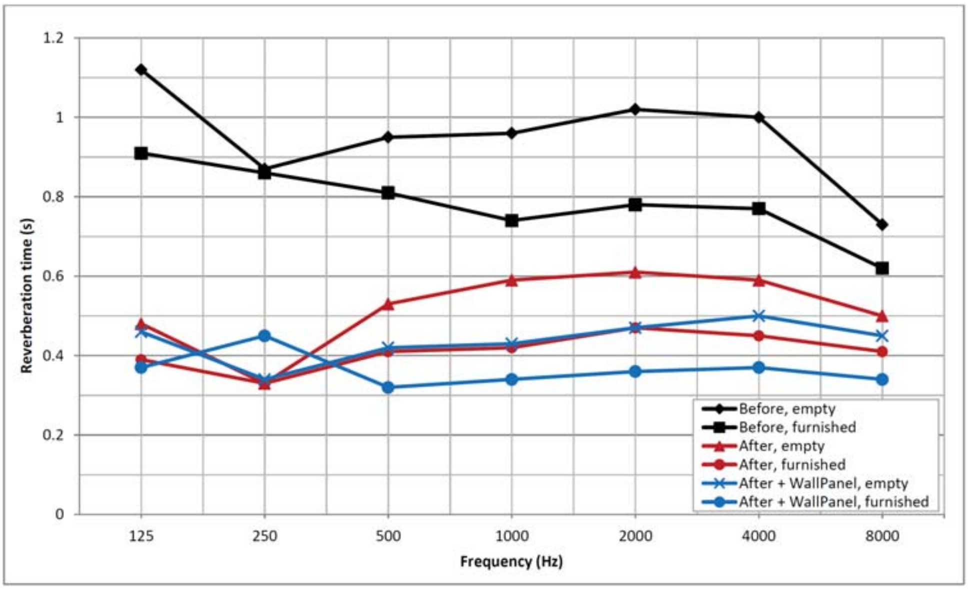


Figure 33: Reverberation times in octave bands of the measured empty and furnished classroom before and after (with and without the wall panel) the acoustical treatment.

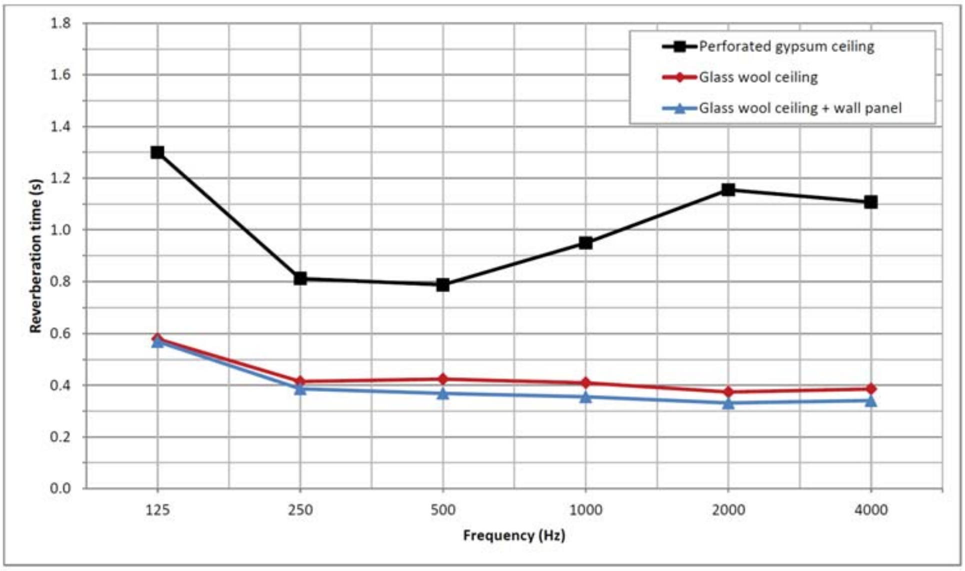
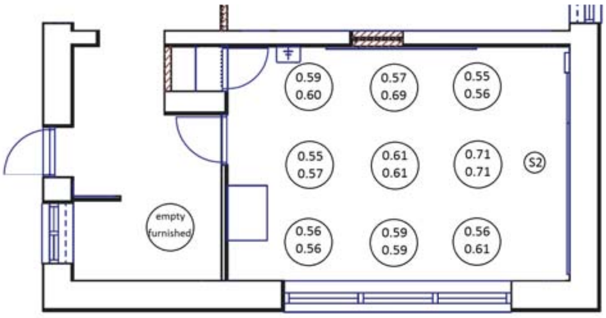


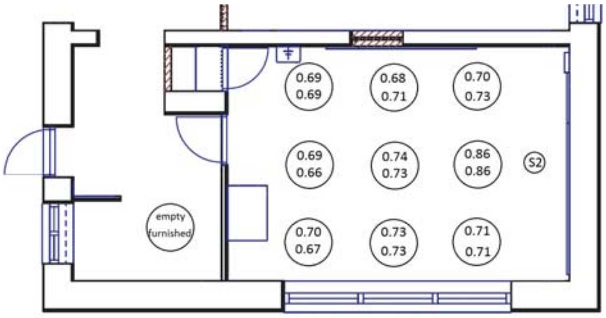
Figure 34: Calculated reverberation times in octave bands of the empty classroom before and after (with and without the wall panel) the acoustical treatment.

The calculated reverberation times (Figure 34) are quite near the actual measured values. However, the effect of the wall panel is much smaller in calculated case than in measured case. Although the calculated values are not exactly the same as the measured values, the calculations could be used to have a rough idea about the magnitude of the reverberation times in the classroom. The fact that the absorptive material is not evenly distributed around the classroom explains the differences between the calculated and the measured values of the reverberation time.

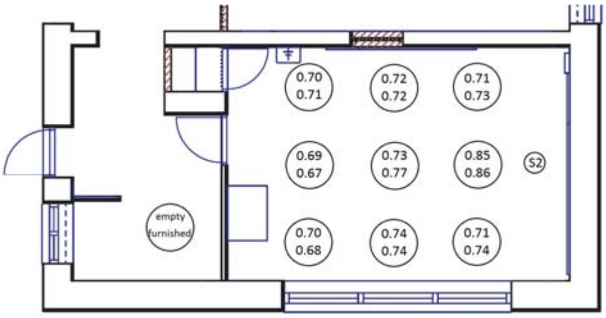
After the acoustical treatment the STI-values in the classroom are generally about 0.15 higher than before the treatment (Figures 35 and 36). The additional wall panel affects mainly to the STI-values in the area near the wall panel increasing them (the values on top of the floor plan in Figure 35c). The change of the STI along the distance is almost constant, thus it is independent from the acoustical treatment (Figure 36).



(a) STI-values of the classroom before the treatment.



(b) STI-values of the classroom after the treatment.



(c) STI-values of the classroom after the treatment with added wall panel.

Figure 35: Speech transmission indices of measured classroom (a) before, (b) after the acoustical treatment and (c) after the treatment with additional absorptive wall panel.

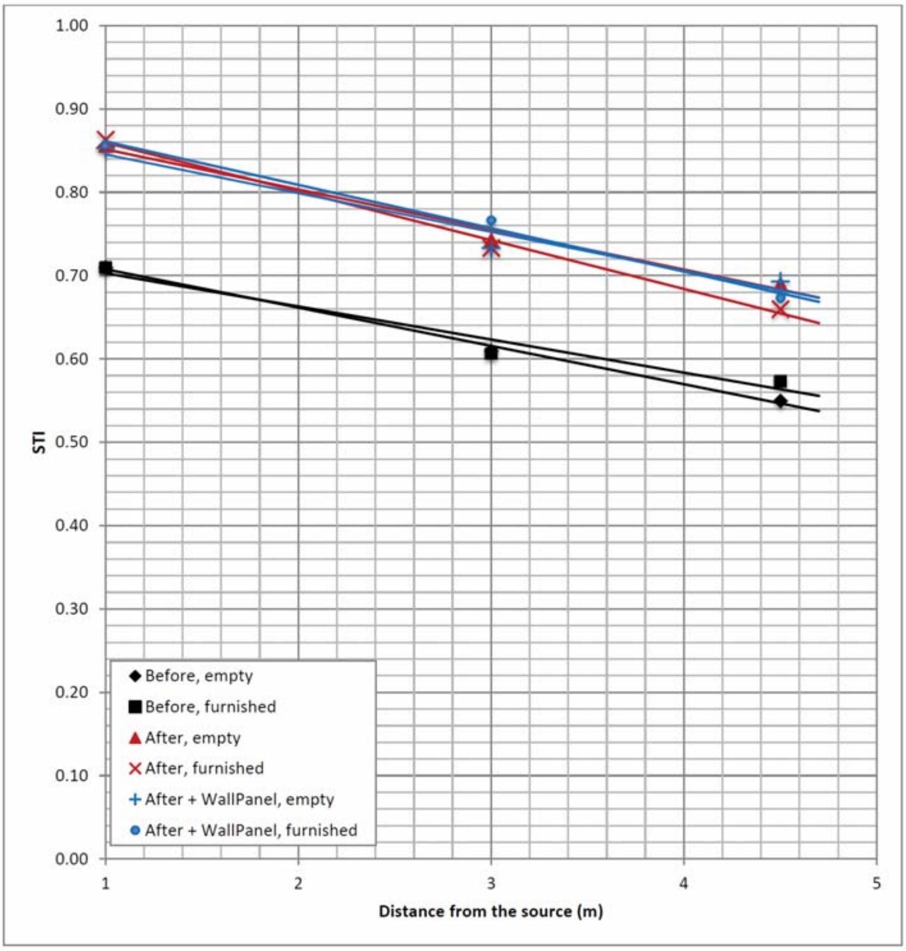


Figure 36: STI-values of the three middle-points (from the teacher position to the door) of empty and furnished classroom before and after (with and without the wall panel) the treatment.

Furniture affects mainly the reverberation time (Figure 33) and the spatial sound distribution (Figure 37). Reverberation times in octave bands have decreased about 0.2 seconds before the treatment due to the furniture and slightly less after the treatment. The decrease is caused by the scattering effect of the furniture (Nilsson et al. 2006; Nilsson 2006), which enhances the absorbing ability of the acoustic ceiling. The value of DL_2 has increased significan after the treatment when the room was furnished. Also, when the additional wall panel was installed, the DL_2-value is still higher in furnished case than in empty case, but the difference is smaller because in empty case the value of DL_2 was already better. Before the treatment the furniture did not have significant effect to the DL_2. The above mentioned scattering effect could be seen also from these results. The STI-values in furnished room in all cases are higher due to the shorter reverberation time, although the difference is very small (Figures 35 and 36). Also, the strength of the furnished room is about 2 dB smaller than in empty room in all cases and clarity is slightly higher in the furnished room before the treatment and slightly lower in the furnished room after the treatment (Table 3). The small differences in clarity values correspond to the small differences in STI-values, as both of them represent the clarity or the distinctness of the speech. Before the treatment clarity and STI values were both slightly higher in furnished case and after the treatment clarity values were lower in furnished case, whereas only some of the STI-values were lower in the corresponding case.

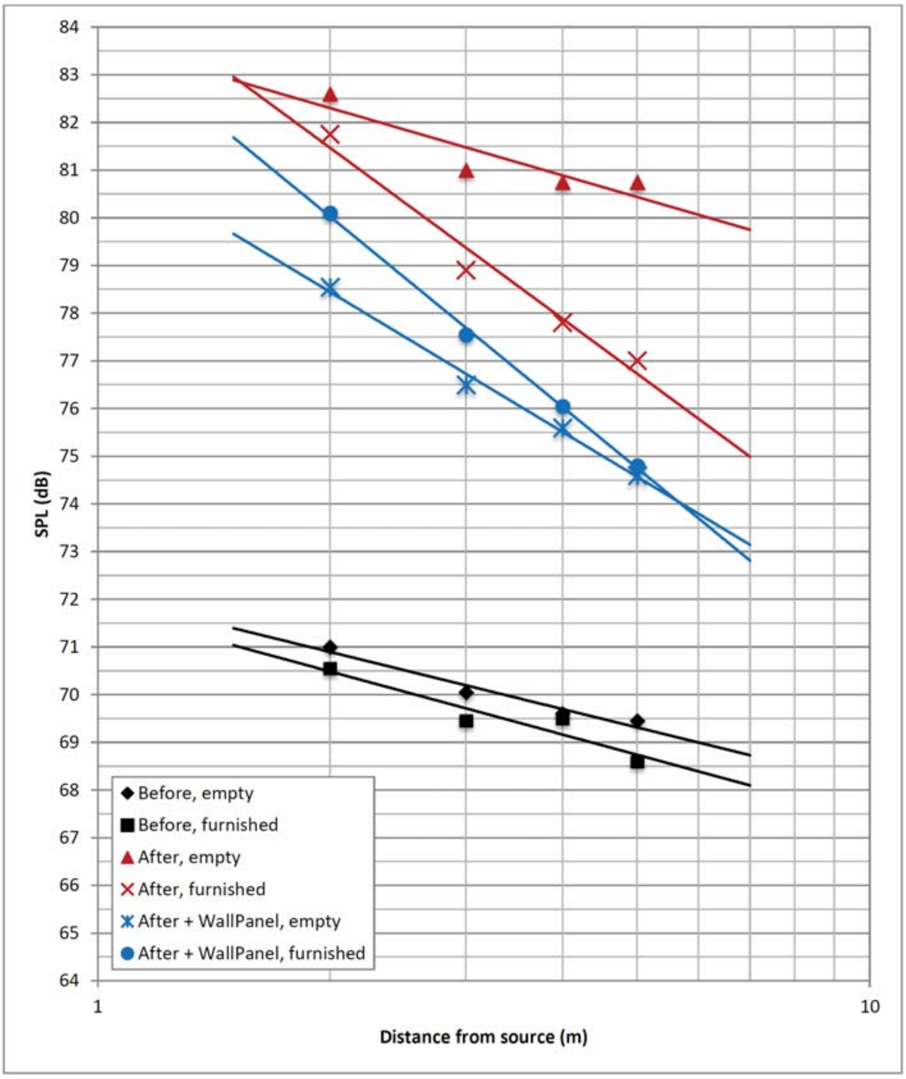


Figure 37: Spatial sound distribution curves of measured empty and furnished classroom before and after (with and without the wall panel) the acoustical treatment. Used sound power level was different in each measurement pair.

The reverberation time of the classroom with perforated gypsum ceiling (Table 3) does not meet the recommendation from standard SFS 5907, which is 0.5 s - 0.6 s (see Section 4.1.1), whether it is furnished or not. STI recommendation from the same standard is 0.80. Classroom with gypsum ceiling clearly does not meet this recommendation either. Even just in front of the teacher the STI is only 0.71 (Figure 35a). After the treatment the reverberation time in empty classroom without the wall panel is 0.57 s, thus it is in the recommended region. However, in empty room with wall panel and in furnished room reverberation times are under 0.5 s, thus they are too short under standard SFS 5907. STI-values in front of the teacher after the treatment are over 0.8 meeting the recommendation in standard SFS 5907, but in other parts of the classroom the values are under 0.8.

Otherwise the acoustical treatment has improved the sound environment of the classroom to the acceptable level but the STI-values in the rear part of the classroom are still too low. One reason to this could be the air conditioning device in the back of the room which creates clearly audible noise. Improvement suggestion for these problems is to encase the air conditioning device, if possible, with noise attenuators at input and output channels.

6.2 Healthcare space

Reverberation times (T_{60}), A-weighted background noise levels (L_{bgA}), and clarity values (C_{50}) of both measured rooms with and without furniture are presented in the Table 4. Also, the reverberation times in octave bands are presented in Figure 38. STI-values of both rooms with and without furniture (in furnished case also with open and closed curtains around the patient's beds) are presented in Figure 40. Expected reverberation times of empty rooms calculated with Sabine's formula (18) are presented in Figure 39. The calculations of reverberation times are presented in Appendix B.

Table 4: Reverberation times (T_{60}), A-weighted background noise levels (L_{bgA}), and clarity values (C_{50}) of the two measured patient rooms, one with glass wool suspended ceiling and another with perforated gypsum suspended ceiling.

	Room with glass wool		**Room with perforated gypsum**	
	empty	**furnished**	**empty**	**furnished**
$\mathbf{T_{60}}$	0.76 s	0.44 s	0.87 s	0.52
$\mathbf{L_{bgA}}$	27.5 dB	27.6 dB	31.4 dB	29.3 dB
$\mathbf{C_{50}}$	6.5 dB	10.5 dB	4.4 dB	7.6 dB

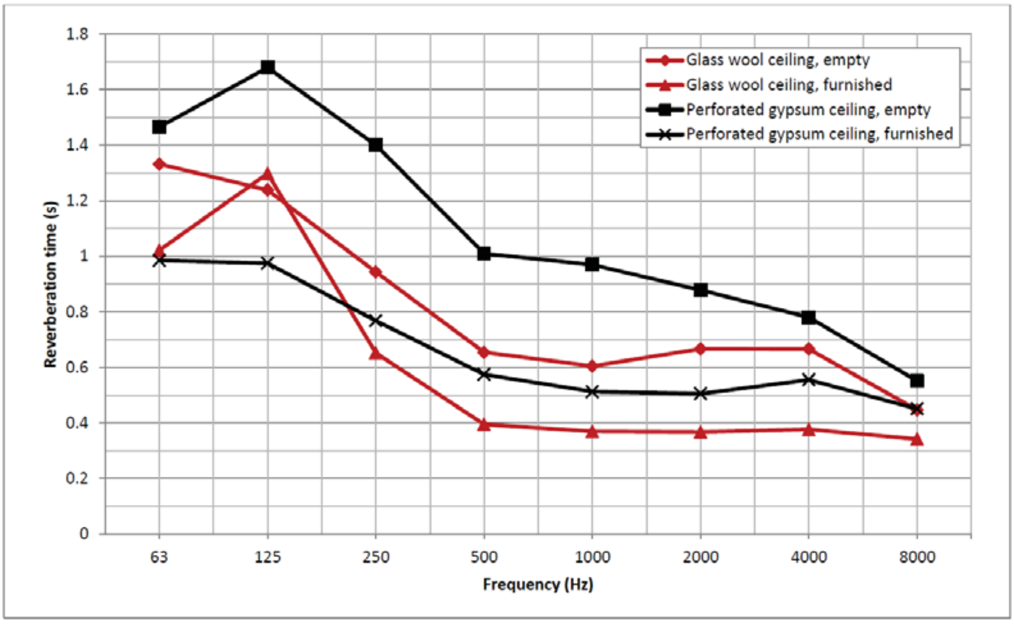


Figure 38: Reverberation times of the two measured patient rooms in octave bands, with and without furniture.

The difference between measured reverberation times in empty cases is clear but not very large (Figure 38). The difference is almost constant at lower frequencies but at the higher frequencies the reverberation times are approaching each other due to glass wool's better ability to absorb low frequencies. Because all the absorption material is placed on the ceiling, in the empty case the horizontal room modes are strong and produce strong reverberation between the walls, thus the ceiling does not affect so much to the reverberation. Sound scattering would cause absorbing ceiling to be more effective, as more sound will reflect to the ceiling (Nilsson et al. 2006; Nilsson 2006). In the empty cases there were practically no scattering objects in the rooms. Thus, the sound field parallel to the ceiling dominates the reverberation making ceiling treatment ineffective (Nilsson 2006). In furnished cases the difference between measured reverberation times is even smaller. Additional furniture, including two beds, acted as an absorbent decreasing the reverberation time. Also, the scattering effect of the furniture enhances the absorbing ability of the ceiling. Especially in the room with perforated gypsum ceiling the reverberation time has decreased significantly.

One reason why the difference of the reverberation times of the gypsum- and glass wool room is quite small is the fact that the difference of absorption indices of perforated gypsum panels and glass wool panels is not very large (Figures 28 and 29 in Appendix A). In Figure 38, the high spike at 125 Hz in the reverberation time of the furnished room with glass wool ceiling is probably an error in measurements, because there should not be any reason why the furniture would increase the reverberation time at one octave band so dramatically. Also, apart from the 125 Hz point, the reverberation time -curve follows the shape of the other curves, thus it refers also to the measurement error.

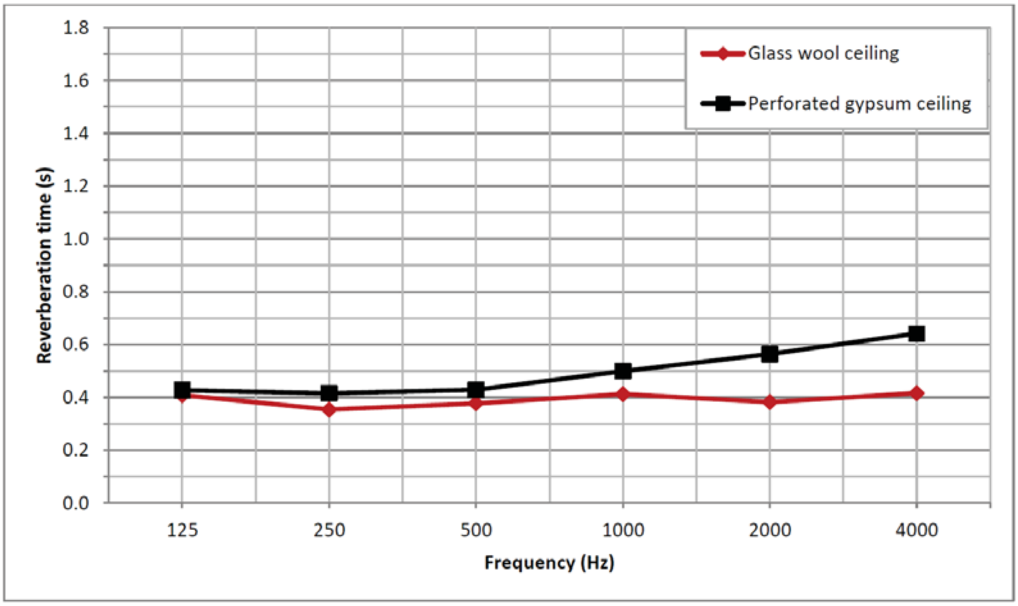


Figure 39: Calculated reverberation times of both empty patient rooms.

The calculated reverberation times of the empty rooms (Figure 39) are very short compared to measured values, especially at lower frequencies (Figure 38). However, with glass wool above 500 Hz the difference between the measured and calculated values is only 0.2 - 0.3 s. Large difference is due to the shape of the room and the placing of the absorption material. Sabine's formula works poorly when the room is low compared to the other dimensions, all the absorption material is placed on the one surface (Rossing 2007; Nilsson 2006) and no scattering objects exist in the room. Thus, the calculated values of reverberation times are not reliable in empty case. However, in the furnished cases above 500 Hz the calculated values of the reverberation time correspond quite well to the measured values. Correspondence is higher due to the furniture, which scatters the sound field preventing the horizontal modes from dominating the overall sound field. Based on these results, the calculations could be used to predict the reverberation times at the higher frequency region, but not in the lower frequency region. Furthermore, the additional furniture have not been taken into account in calculations as an additional absorption area. Adding the absorption area of the furniture would decrease the calculated values of the reverberation time even more, leading to more unrealistic results.

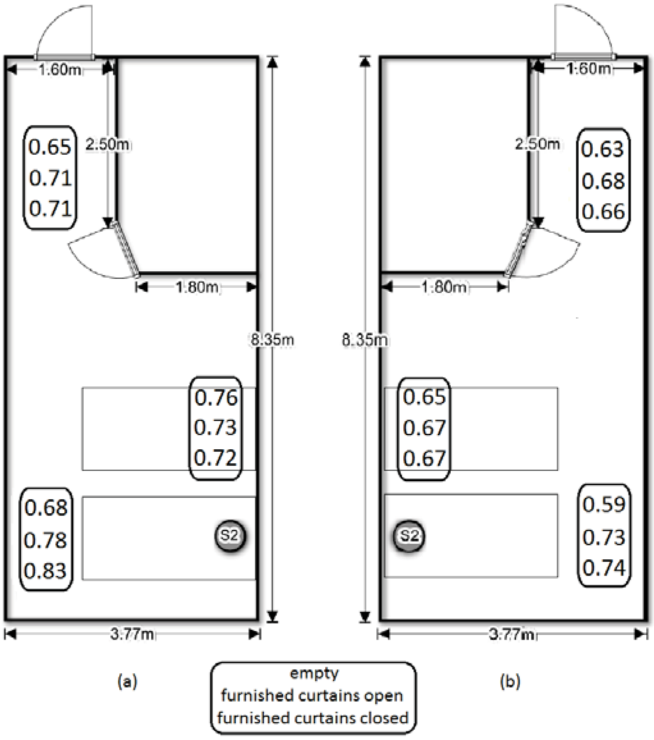


Figure 40: Speech transmission indices of both measured patient rooms, empty and furnished with open and closed curtains. (a) The room with the glass wool ceiling. (b) The room with the perforated gypsum ceiling.

Speech transmission index values are clearly smaller in the room with the perforated gypsum ceiling (Figures 40 and 41), although the difference is rather small, especially when the rooms were empty. In the empty cases the background noise level in the room with gypsum ceiling was higher (Table 4) and the reverberation time was longer (Table 4 and Figure 38). These are the main factors decreasing the STI-values, thus the longer reverberation time is not alone responsible for the lower

STI-values. In furnished cases STI-values are still higher in the room with glass wool ceiling but the difference is smaller. The background noise level in the room with gypsum ceiling was still slightly higher but now the difference of the reverberation times was smaller. This causes the difference of the STI-values between the two rooms to be smaller than in empty cases. The effect of the curtains around the patient's beds to the STI-values is negligible.

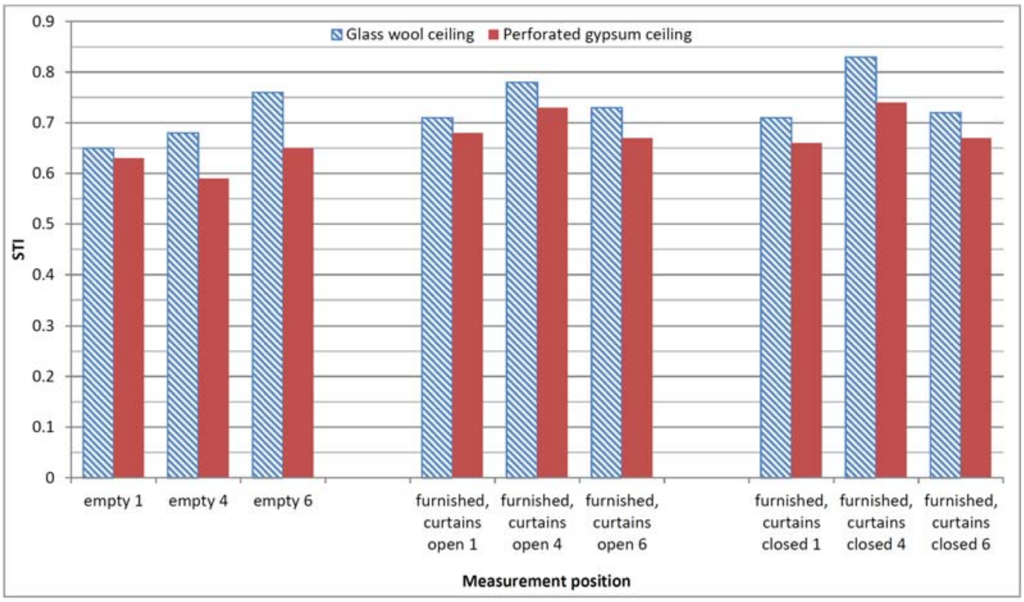


Figure 41: Speech transmission indices of both measured patient rooms, empty and furnished with open and closed curtains. Measurement position numbering is presented in Figure 27.

Unlike speech transmission index, clarity is independent from background noise level. Thus, clarity could be used to determine the speech intelligibility in empty and furnished cases regardless of the background noise levels. In empty case clarity is 1.1 dB higher in the room with glass wool ceiling (Table 4), meaning that the speech clarity is still greater, whether the background noise is present or not. In furnished case clarity is 2.9 dB higher in the room with glass wool ceiling. This implies that the glass wool ceiling improves speech intelligibility greatly when the furniture in the room enhances the absorbing ability of the ceiling. Furthermore, in both rooms the value of clarity has increased due to the furniture's scattering effect.

The recommendation for the patient room reverberation time in standard SFS 5907 is 0.6 s (see Section 4.1.2), thus both rooms have too long reverberation time when they are empty, but when furnished the reverberation times meet the standard recommendation (Table 4). Background noise levels in room with glass wool ceiling meet the recommendations from WHO and SFS 5907, which are 30 dB and 29 dB correspondingly (see Section 4.1.2). In the room with gypsum ceiling the background noise levels are slightly higher than in the recommendations. However, the measured values exceed the recommendations only less than 2 dB. In the empty room measurements the hospital building was still under construction, so the furnished room background noise levels correspond more to the reality.

In patient's rooms the low STI-values between the beds are desirable to provide privacy to the patients. This sets a contradiction with the reverberation time, because decreasing the reverberation time will increase the speech transmission index. Solution to this could be heavy curtains installed between the patients and absorption panels installed to the wall opposite to the beds of patients. Curtain will reduce the direct sound from patient to another and the absorption panels will reduce the reflections between the patients. On the other hand, a communication should be possible between the patients if necessary, thus the sound insulating structure between the patients should be mobile or foldaway.

6.3 Open plan office

Reverberation times (of room 338) (T_{60}), A-weighted background noise levels (L_{bgA}), DL_2-values, distraction distances (r_d), strength values (G) (of room 338), and clarity values (C_{50}) (of room 338) before and after acoustical treatment are presented in Table 5. STI-values before and after the treatment are presented in Figure 42, reverberation times in octave bands of the room 338 are presented in Figure 44, and STI and DL_2 -curves of the entire office are illustrated in Figures 43 and 47 correspondingly. Sound pressure levels in each measurement position, before and after the treatment, are illustrated in Figures 45 and 46. Expected DL_2 and r_d -values and STI-curves of the room 338 and the whole office calculated with Finnish Institute of Occupational Health open plan office modelling tool (Keränen et al. 2007), (`http://www.ttl.fi/en/work_environment/physical_factors/acoustictool/`) are presented in Figures 49 and 48 correspondingly.

Table 5: Reverberation times (T_{60}) (of room 338), A-weighted background noise levels (L_{bgA}), DL_2-values, strength values (G) (of room 338), distraction distances (r_d), and clarity values (C_{50}) (of room 338) of the measured open plan office before and after acoustical treatment.

	Before	**After**
$\mathbf{T_{60}}$	0.39 s	0.29 s
$\mathbf{L_{bgA}}$	30.4 dB	30.1 dB
$\mathbf{DL_2}$	18.2 dB	20.7 dB
$\mathbf{r_d}$	5.3 m	4.2 m
G	16.3 dB	13.0 dB
$\mathbf{C_{50}}$	8.0 dB	10.4 dB

Speech transmission index values in room 338 has remained fairly constant except at the measurement point 2 (Figure 30, above the sound source) the value has increased 0.07 after the treatment (Figure 42). That is probably due to the decreased reverberation time as the background noise level has remained constant (Table 5). At the first position in room 339 (point 7 in Figure 30) the STI-value has decreased significantly, 0.32, and at the rest positions (point 8 and 9 in Figure 30) STI-values have also decreased 0.12 and 0.13 correspondingly (see Figure 42). The reason to this is the large absorptive wall panel installed on the corridor wall. Before the treatment sounds from the room 338 were reflected to the rooms 339 and 340 directly from the hard corridor wall. After the treatment the installed wall panel absorbs the majority of the sounds from the room 338. STI-values of measurement positions 2, 7, 8, and 9 before and after the treatment are also illustrated in the Figure 43. The sound insulation of the unused door between rooms 338 and 339 was poor, thus insulating the door would decrease the STI values in room 339 even more.

The value of the clarity in the room 338 after the treatment has increased 2.4 dB (Table 5), whereas the STI-values have remained fairly constant (Figure 42). This

(a) Before

(b) After

Figure 42: Speech transmission indices of measured open plan office (a) before and (b) after the acoustical treatment. Sound source is marked with S1.

indicates that the total distinctness of the speech in the room 338 has improved, even though the STI-values have not changed significantly.

The distraction distances of the whole office before and after the treatment (Table 5) are very short. The actual walls between different office rooms affect to the STI-values decreasing them, thus decreasing the distraction distance. The wall panel on the corridor wall decreases STI-values decreasing also the distraction distance. The distraction distance measured inside only one office room at the time would be greatly longer. Because of the actual walls between the office rooms the distraction distances of the office are not comparable with distraction distances of traditional open plan offices. The distraction distances of the office have been determined from the Figure 43.

The reverberation time of the room 338 was already rather short and it was decreased by 0.1 s (Table 5) after the treatment. The difference is small but clear and because the reverberation time was already short the difference is not expected to be very large. The change of the reverberation time in octave bands was also clear (Figure 44). Above 500 Hz the difference is nearly constant, 0.15 s, and below

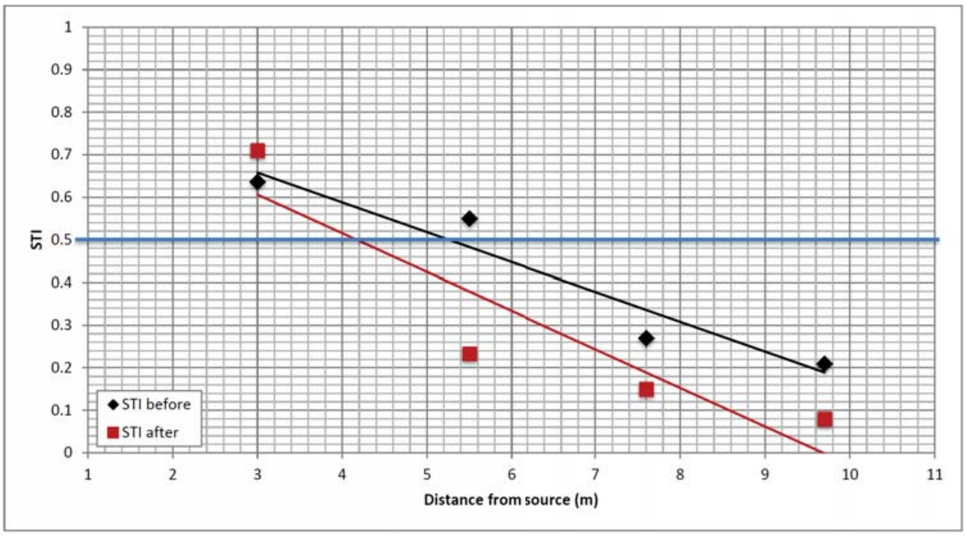


Figure 43: Speech transmission indices of measured open plan office before and after the acoustical treatment (measurement points 2, 7, 8, and 9).

500 Hz the difference is larger, except 63 Hz band. Before the treatment the office contained fairly poor absorbing screens and the ceiling as only absorption materials, so the absorption at higher frequencies was greater because the space did not contain practically any low frequency absorbing materials. After the treatment the installed wall panels improved the low frequency absorption and it could be seen as a decrease of the reverberation time at lower frequencies in Figure 44. Reverberation was not a problem in the office, whereas the excessive sound spreading was, thus the reverberation time does not offer much additional information in this context.

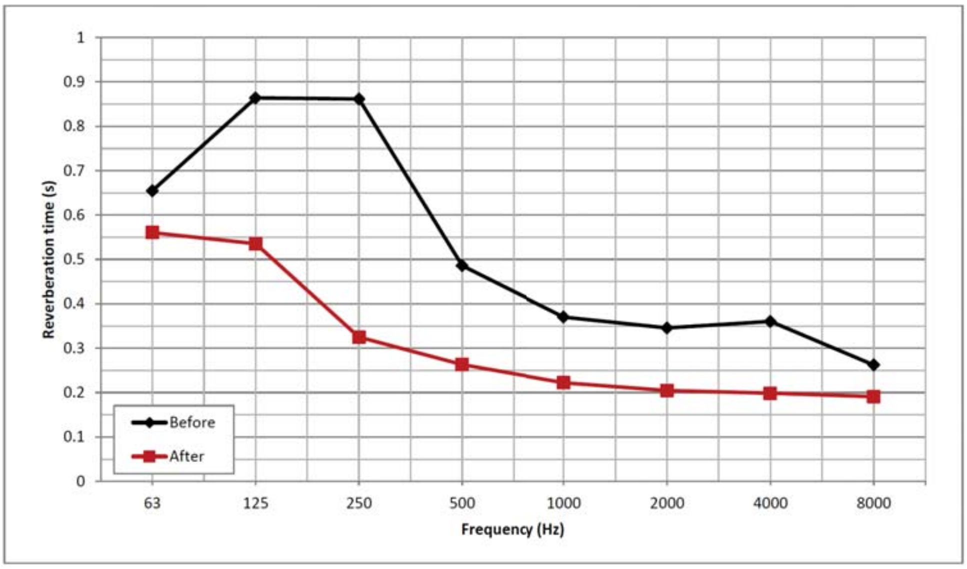


Figure 44: Reverberation times of the measured open plan office before and after the acoustical treatment.

Installed absorption panels have decreased sound pressure levels of the entire office by 2-8 dB (Figures 45 and 46). Sound pressure levels have decreased 2-4 dB in the room 338 when using sound source S1. Additionally, as it could be seen from Figures 45 and 46, sound pressure level decreases the more the further away from the sound source it is measured. In the furthest office room (number 340) the difference is already 6 dB. This implies that the sound propagation from one office room to another has reduced significantly. For example, in Figure 46 the difference of sound pressure levels is even 8 dB between rooms 336 and 338.

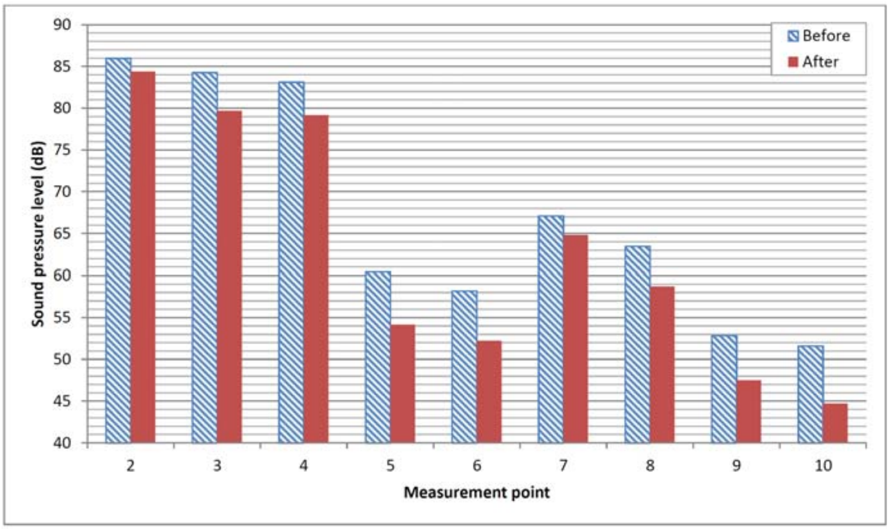


Figure 45: A-weighted sound pressure levels in measurement positions 2-10 using source S1 (see Figure 30 for position numbering) before and after the acoustical treatment.

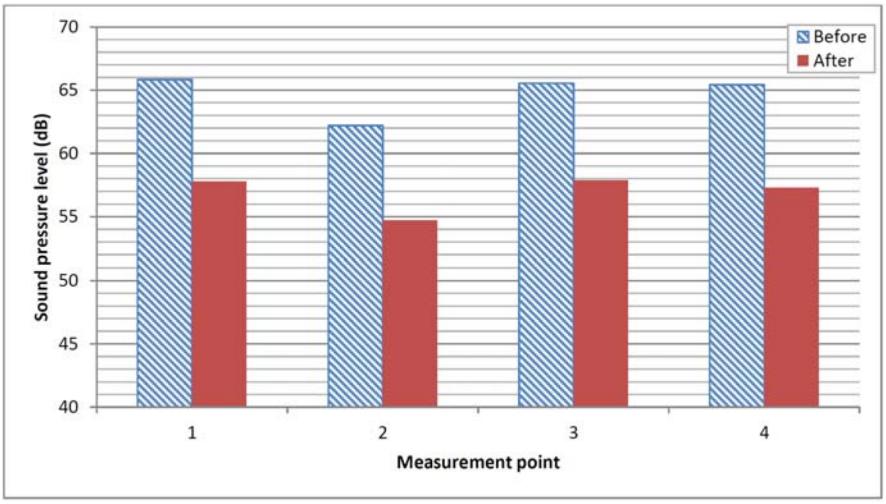
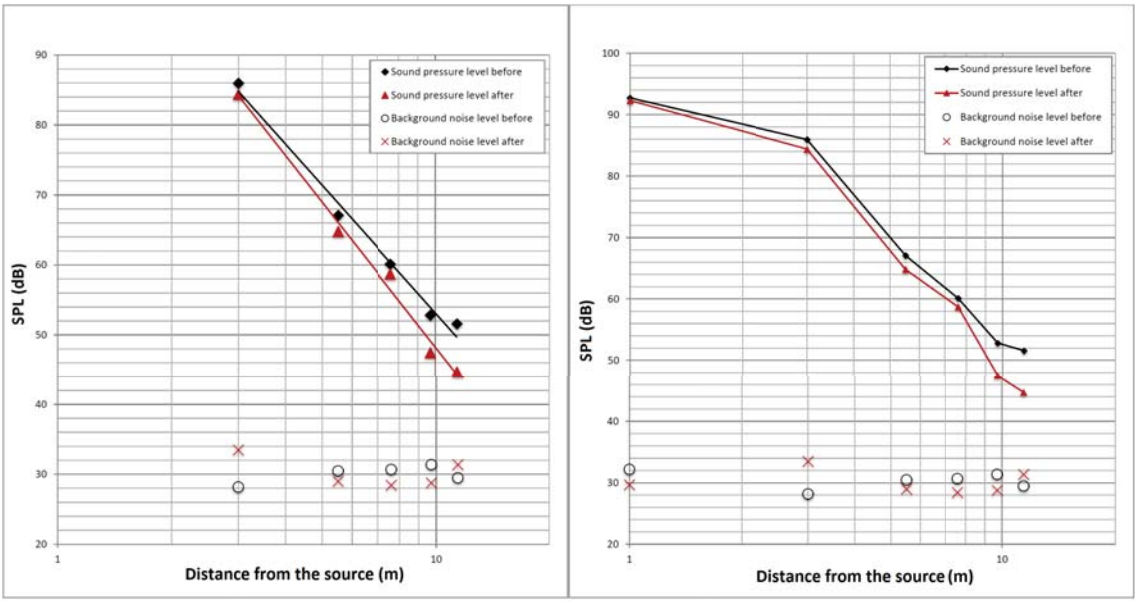


Figure 46: A-weighted sound pressure levels in measurement positions 1-4 using source S2 (see Figure 30 for position numbering) before and after the acoustical treatment.

DL_2-value of the entire office has increased by 2.5 dB, which is not a very large difference (Table 5). The value of DL_2 of the entire office was already very high due to the actual walls between the office rooms. The presence of the walls could be seen from Figure 47 (b) where the sound pressure level decreases rapidly after every two consecutive points in both curves. Because the floor plan of the measured office is not a traditional open plan office floor plan, the DL_2 results are not comparable with traditional open office results.

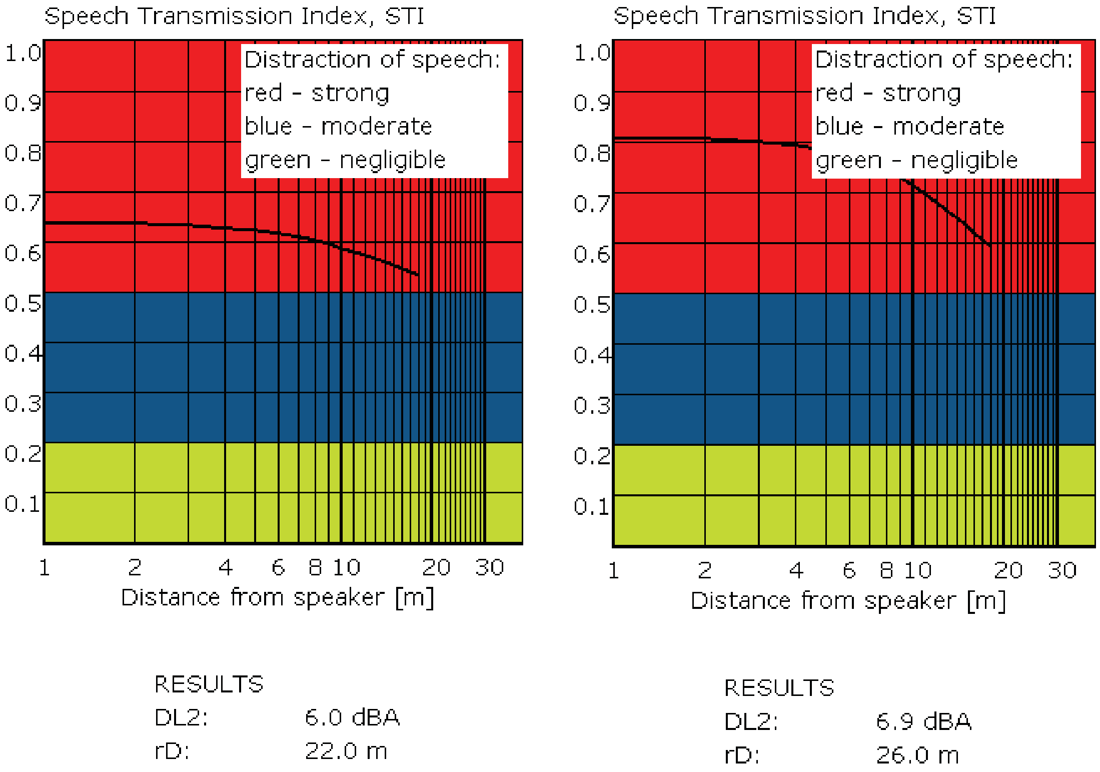


(a)

(b)

Figure 47: Spatial sound distribution curves of measured open plan office before after the acoustical treatment. (a) Linear fitting to determine the DL_2-value. (b) Sound pressure levels versus distance from the source.

The modelled values of DL_2 of the entire office (Figure 48) are very small compared to measured values (Table 5), because the model assumes the space to be a traditional open office, which the measured office is not. Therefore, the modelled results are not reliable when considering the entire office. However, when analysing only one individual room the model produces results (Figure 49), which are quite near the measured results (Table 6). In Figure 50 are illustrated spatial sound distribution curves of room 338 before and after the treatment. The figure includes two pairs of curves, the first pair is spatial sound distribution measured at positions 1 and 2, and the second pair is measured at positions 1 and 4 (see Figure 30 for position numbering). The corresponding DL_2-values are presented in Table 6. These values of DL_2 are remarkably smaller than the corresponding values of the entire office (Table 5) and correspond more to values of traditional open plan offices. Furthermore, when comparing the modelled DL_2-values of the room 338 (Figure 49) to the measured values (Table 6) it could be seen that they are close to each other, so in this case the model produces more reliable results. However, determining DL_2 based on measurements at only two points is inaccurate and not very reliable. That could be seen from Figure 50, where the curves of different measurement paths differ from each other.



(a) Before

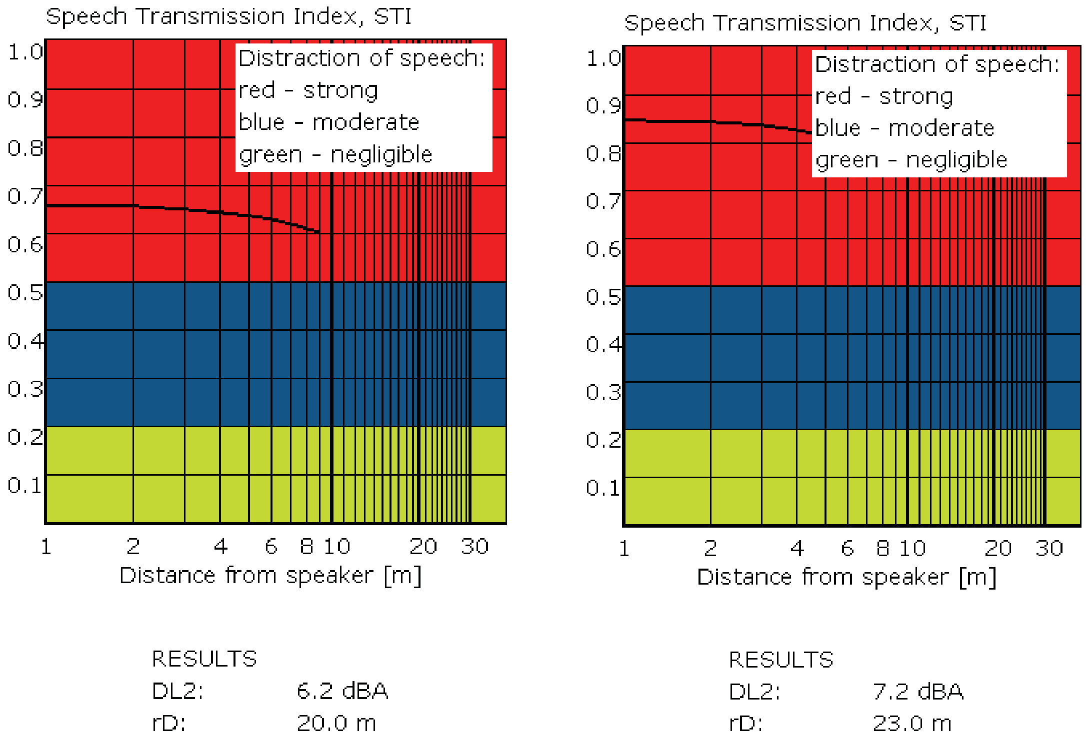
(b) After

Figure 48: Calculated values of DL_2, r_d, and STI of entire office before and after the acoustical treatment. Open plan office modelling tool (Keränen et al. 2007).

Table 6: Measured DL_2 values of the room 338 before and after the treatment in two different paths.

	Points 1 - 2		**Points 1 - 4**	
	Before	**After**	**Before**	**After**
DL_2	4.3 dB	5.0 dB	4.7 dB	6.3 dB

The realized acoustical treatment has clearly improved the sound environment in the measured open plan office by decreasing the reverberation time, decreasing speech intelligibility between rooms, decreasing sound propagation from work space to another, and lowering the overall sound pressure levels. Especially the absorptive wall panel in the corridor has a large impact on attenuating the sounds between the office rooms. The decreased reverberation time could make phone using more pleasant in the office. However, the clarity of speech in the room 338 has increased. This could be desirable if all workers in the room collaborated, but if they do independent work the increased clarity could be distracting. Further actions to improve the sound environment even more could be to insulate all the unused doors between the office rooms and use free hanging absorption units, if possible, to increase the total absorption area.



```
RESULTS
DL2:        6.2 dBA
rD:         20.0 m
```

```
RESULTS
DL2:        7.2 dBA
rD:         23.0 m
```

(a) Before

(b) After

Figure 49: Calculated values of DL_2, r_d, and STI of office room 338 before and after the acoustical treatment. Open plan office modelling tool (Keränen et al. 2007).

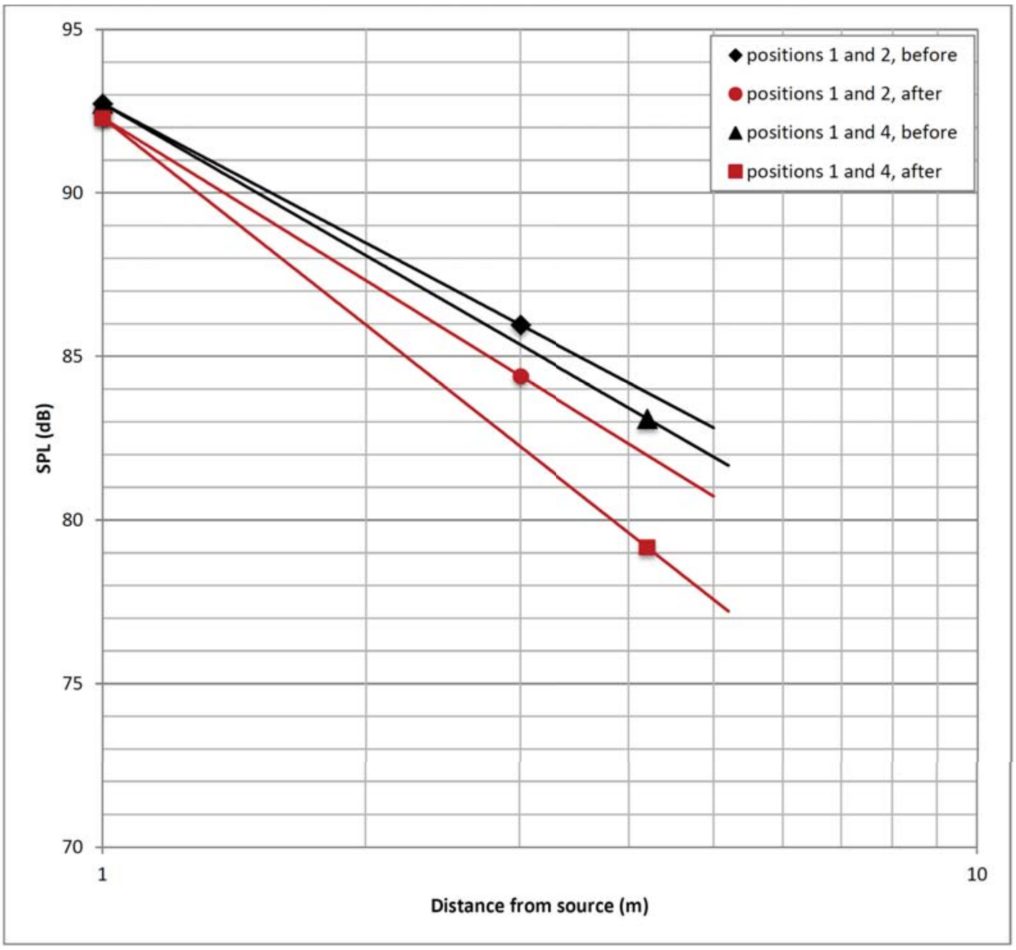


Figure 50: Spatial sound distribution curves of room 338 of the measured office before and after the treatment. See Figure 30 for the measurement position numbering.

7 Conclusions

In this thesis the effects of the acoustical treatment to the sound environment of the three types of public spaces were studied. The places were a classroom in a comprehensive school, a patient room in medical center, and an open plan office. The acoustical renovation was performed to the classroom and to the open plan office and the measurements were made before and after the renovation. In medical center, two identical patient rooms with different acoustical treatment were measured.

The acoustical treatment has clearly improved the sound environment in the each type of space covered by this thesis. The working environment has improved in the treated spaces and they are now more comfortable to be in than before. As a continuation for the research a subjective part should be performed in the measured spaces by interviewing the employees and the patients about the sound environment and the acoustics of the space, and how it affects to the general work environment. Generally the employees of the treated spaces were satisfied about the acoustics but the real and more accurate survey should be done.

The classroom had a suspended perforated gypsum ceiling before the treatment, and after the treatment it contained a suspended glass wool ceiling with additional bass absorbers on top of it and a large absorptive wall panel. The sound environment has improved significantly after the acoustical treatment. The reverberation time was shortened greatly, 0.4 s - 0.5 s in every frequency band. Furthermore, the values of speech transmission index were increased by 0.15 everywhere in the room and the values of clarity were increased by over 6 dB. The effect of the additional installed bass absorbers could also be seen from the decreased reverberation times at the low frequency region where the reverberation time has decreased 0.5 s. The installed absorptive wall panel increased the overall absorption area decreasing the reverberation time but also it removed the flutter echo between the side walls. Now the classroom fulfils the standard SFS 5907 recommendation for the reverberation time. STI-values in the front part of the classroom are also in accordance with the standard recommendations, but in the rear part the values are too low. The speech intelligibility could be improved further by muting the air conditioning device, because the reverberation time is already quite low. However, STI-values will be increased slightly when pupils are in the classroom. Wall-to-wall carpet would also reduce the noise from moving chairs and tables.

The first of the measured patient rooms contained a suspended glass wool ceiling and the second room contained a suspended perforated gypsum ceiling. The sound environment in the room with the glass wool ceiling was clearly better than in the room with the perforated gypsum ceiling. The reverberation times were lower in every frequency band and STI and clarity -values were higher in the room with the glass wool ceiling. High speech intelligibility in the patient room is desirable when considering the discussion between the doctor and the patient, whereas it is not desirable when considering the privacy of the patients. When furnished, both rooms meet the Finnish standard SFS 5907 recommendation for the reverberation time. However, the room with the gypsum ceiling do not meet the recommendation for the background noise level from the same standard, but the difference is less than 1 dB.

Furniture clearly improved the efficiency of the acoustical ceiling by scattering the sound field in the room. The curtains around the patient's beds did not affect to the speech intelligibility. The privacy between the patients could be improved by using mobile or foldaway screens or heavy curtains between the beds. Also, additional absorbing wall panels could reduce unwanted reflections from one bed to another. The differences of acoustic between the two rooms were clear but not remarkably large. One reason to this is that the difference between absorbing abilities of the used glass wool panel and the perforated gypsum panel was not remarkably large either.

The open plan office had already an acoustical spray coating as a ceiling and high screens between the workstations. In the renovation, absorptive wall panels were installed to practically every wall from table height to the ceiling. The major problem in the office was sound propagation from a work station to another. After the treatment the STI-values between the workstations and especially between the office rooms decreased. Furthermore, the overall sound pressure level was decreased, thus the whole office is now more silent. The decrease of sound pressure level between the office rooms was significant, in some cases even 8 dB. The reverberation time decreased also slightly but it was not the problem before the treatment either as it was already in an acceptable level. Although, the improvement in the reverberation time of the low frequency region was larger. The rate of spatial decay of sound pressure level per distance doubling was also increased slightly, but as the measured office was not a traditional open plan office the DL_2 values do not represent the acoustical properties of the space well. The spreading of sound could be prevented further by sealing the unused doors between the office rooms. At present condition the doors leak noise greatly. Because the building is conserved and installing the acoustical ceiling is therefore not an option, the free hanging acoustical units could be used to further increase the absorption area in the office room, thus decrease the sound pressure levels even more.

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A Classroom: Pictures of the measured spaces, and the reverberation time calculations

Pictures of the measured classroom

(a) From the front door.

(b) From the back wall.

Figure A1: Measured empty classroom before the treatment with Gyptone BIG Quattro 47 suspended ceiling.

(a) From the front door.

(b) From the back wall.

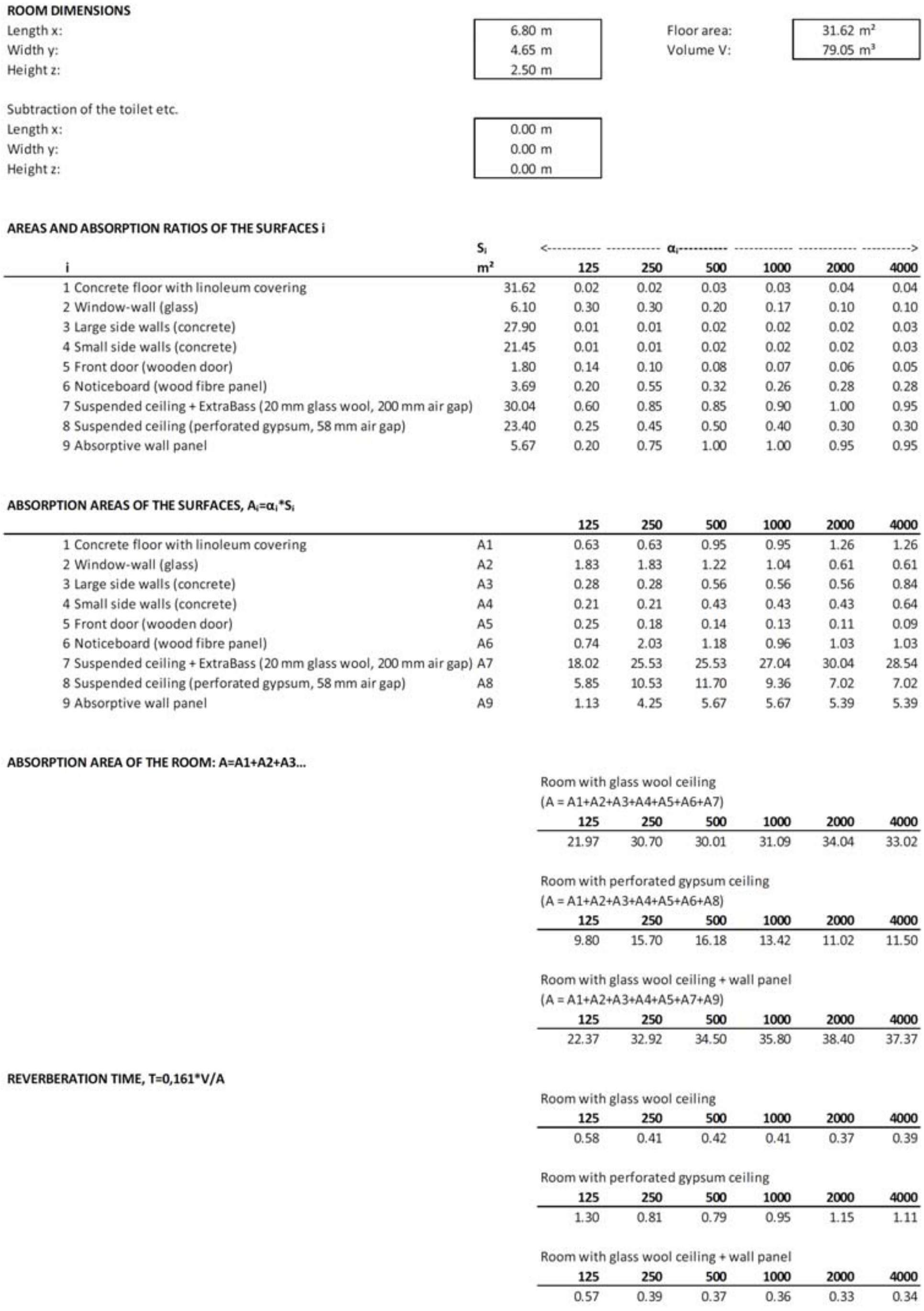
Figure A2: Measured furnished classroom before the treatment with Gyptone BIG Quattro 47 suspended ceiling.

(a) After the treatment.

(b) Extra Bass solution.

Figure A3: (a) Measured empty classroom after the acoustical treatment with Ecophon Master Rgid Dp and (b) bass absorbers above the ceiling.

The reverberation time calculations of the classroom



ROOM DIMENSIONS

Length x:	6.80 m	Floor area:	31.62 m^2
Width y:	4.65 m	Volume V:	79.05 m^3
Height z:	2.50 m		

Subtraction of the toilet etc.

Length x:	0.00 m
Width y:	0.00 m
Height z:	0.00 m

AREAS AND ABSORPTION RATIOS OF THE SURFACES i

i	S_i m^2	125	250	500	1000	2000	4000
		<-----------	-----------	α_i----------	-----------	-----------	---------->
1 Concrete floor with linoleum covering	31.62	0.02	0.02	0.03	0.03	0.04	0.04
2 Window-wall (glass)	6.10	0.30	0.30	0.20	0.17	0.10	0.10
3 Large side walls (concrete)	27.90	0.01	0.01	0.02	0.02	0.02	0.03
4 Small side walls (concrete)	21.45	0.01	0.01	0.02	0.02	0.02	0.03
5 Front door (wooden door)	1.80	0.14	0.10	0.08	0.07	0.06	0.05
6 Noticeboard (wood fibre panel)	3.69	0.20	0.55	0.32	0.26	0.28	0.28
7 Suspended ceiling + ExtraBass (20 mm glass wool, 200 mm air gap)	30.04	0.60	0.85	0.85	0.90	1.00	0.95
8 Suspended ceiling (perforated gypsum, 58 mm air gap)	23.40	0.25	0.45	0.50	0.40	0.30	0.30
9 Absorptive wall panel	5.67	0.20	0.75	1.00	1.00	0.95	0.95

ABSORPTION AREAS OF THE SURFACES, $A_i=\alpha_i*S_i$

		125	250	500	1000	2000	4000
1 Concrete floor with linoleum covering	A1	0.63	0.63	0.95	0.95	1.26	1.26
2 Window-wall (glass)	A2	1.83	1.83	1.22	1.04	0.61	0.61
3 Large side walls (concrete)	A3	0.28	0.28	0.56	0.56	0.56	0.84
4 Small side walls (concrete)	A4	0.21	0.21	0.43	0.43	0.43	0.64
5 Front door (wooden door)	A5	0.25	0.18	0.14	0.13	0.11	0.09
6 Noticeboard (wood fibre panel)	A6	0.74	2.03	1.18	0.96	1.03	1.03
7 Suspended ceiling + ExtraBass (20 mm glass wool, 200 mm air gap)	A7	18.02	25.53	25.53	27.04	30.04	28.54
8 Suspended ceiling (perforated gypsum, 58 mm air gap)	A8	5.85	10.53	11.70	9.36	7.02	7.02
9 Absorptive wall panel	A9	1.13	4.25	5.67	5.67	5.39	5.39

ABSORPTION AREA OF THE ROOM: A=A1+A2+A3...

Room with glass wool ceiling
(A = A1+A2+A3+A4+A5+A6+A7)

125	250	500	1000	2000	4000
21.97	30.70	30.01	31.09	34.04	33.02

Room with perforated gypsum ceiling
(A = A1+A2+A3+A4+A5+A6+A8)

125	250	500	1000	2000	4000
9.80	15.70	16.18	13.42	11.02	11.50

Room with glass wool ceiling + wall panel
(A = A1+A2+A3+A4+A5+A7+A9)

125	250	500	1000	2000	4000
22.37	32.92	34.50	35.80	38.40	37.37

REVERBERATION TIME, T=0,161*V/A

Room with glass wool ceiling

125	250	500	1000	2000	4000
0.58	0.41	0.42	0.41	0.37	0.39

Room with perforated gypsum ceiling

125	250	500	1000	2000	4000
1.30	0.81	0.79	0.95	1.15	1.11

Room with glass wool ceiling + wall panel

125	250	500	1000	2000	4000
0.57	0.39	0.37	0.36	0.33	0.34

Figure A4: The reverberation time calculations of measured classroom before and after the acoustical treatment. Absorption indices are from (Halme and Seppänen 2002).

B Healthcare space: Pictures of the measured spaces, and the reverberation time calculations

Pictures of the measured healthcare spaces

(a) From the front door.

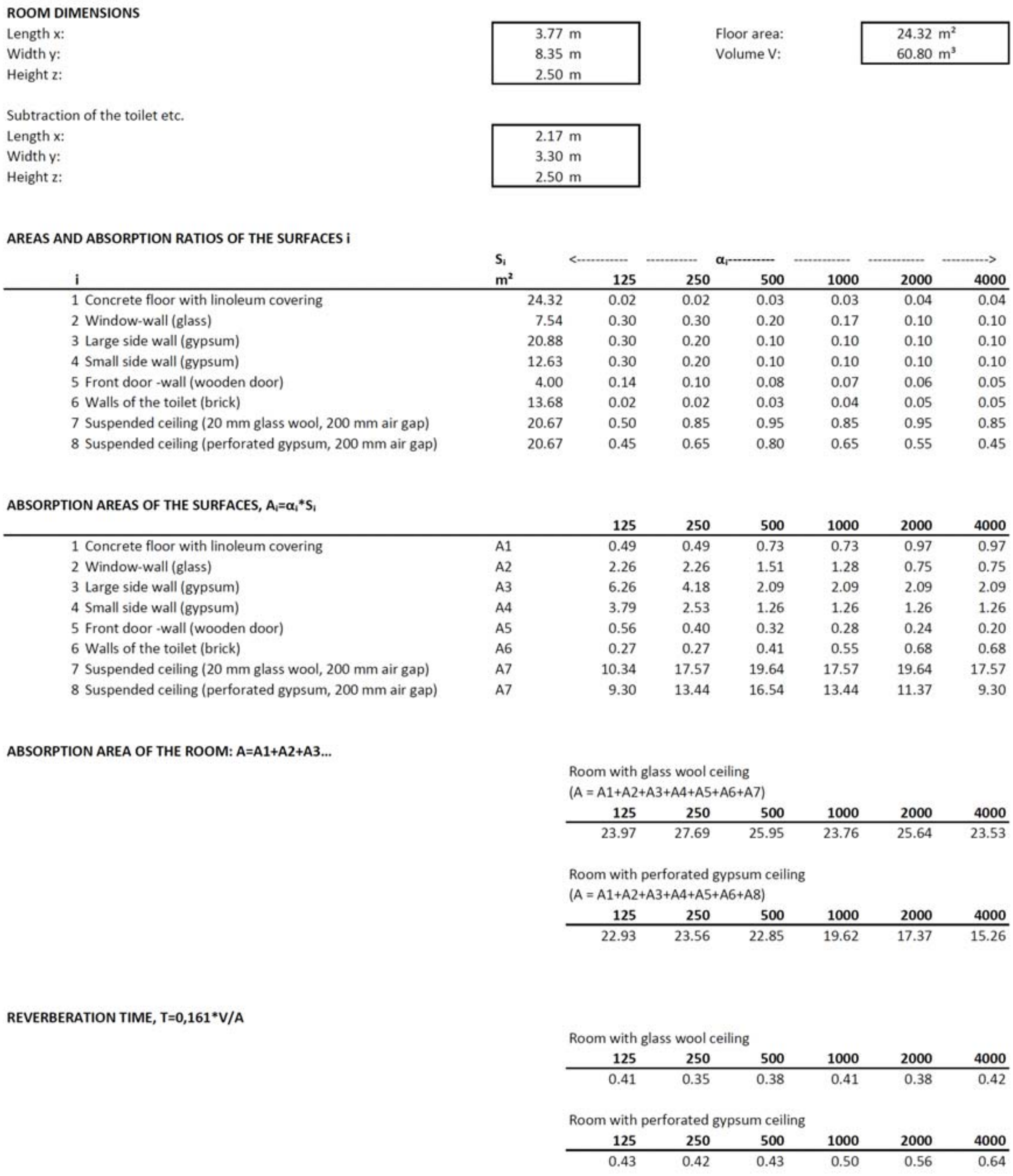
(b) From the window wall.

Figure B1: Measured patient room with glass wool Ecophon Focus A suspended ceiling.

(a) From the front door. (b) From the window wall.

Figure B2: Measured patient room with perforated gypsum Knauf Plaza G1 suspended ceiling.

The reverberation time calculations of the measured health-care spaces



ROOM DIMENSIONS

Length x:	3.77 m	Floor area:	24.32 m²
Width y:	8.35 m	Volume V:	60.80 m³
Height z:	2.50 m		

Subtraction of the toilet etc.

Length x:	2.17 m
Width y:	3.30 m
Height z:	2.50 m

AREAS AND ABSORPTION RATIOS OF THE SURFACES i

	S_i	<-----------	-----------	α_i----------	------------	------------	---------->
i	**m²**	**125**	**250**	**500**	**1000**	**2000**	**4000**
1 Concrete floor with linoleum covering	24.32	0.02	0.02	0.03	0.03	0.04	0.04
2 Window-wall (glass)	7.54	0.30	0.30	0.20	0.17	0.10	0.10
3 Large side wall (gypsum)	20.88	0.30	0.20	0.10	0.10	0.10	0.10
4 Small side wall (gypsum)	12.63	0.30	0.20	0.10	0.10	0.10	0.10
5 Front door -wall (wooden door)	4.00	0.14	0.10	0.08	0.07	0.06	0.05
6 Walls of the toilet (brick)	13.68	0.02	0.02	0.03	0.04	0.05	0.05
7 Suspended ceiling (20 mm glass wool, 200 mm air gap)	20.67	0.50	0.85	0.95	0.85	0.95	0.85
8 Suspended ceiling (perforated gypsum, 200 mm air gap)	20.67	0.45	0.65	0.80	0.65	0.55	0.45

ABSORPTION AREAS OF THE SURFACES, $A_i=\alpha_i*S_i$

		125	250	500	1000	2000	4000
1 Concrete floor with linoleum covering	A1	0.49	0.49	0.73	0.73	0.97	0.97
2 Window-wall (glass)	A2	2.26	2.26	1.51	1.28	0.75	0.75
3 Large side wall (gypsum)	A3	6.26	4.18	2.09	2.09	2.09	2.09
4 Small side wall (gypsum)	A4	3.79	2.53	1.26	1.26	1.26	1.26
5 Front door -wall (wooden door)	A5	0.56	0.40	0.32	0.28	0.24	0.20
6 Walls of the toilet (brick)	A6	0.27	0.27	0.41	0.55	0.68	0.68
7 Suspended ceiling (20 mm glass wool, 200 mm air gap)	A7	10.34	17.57	19.64	17.57	19.64	17.57
8 Suspended ceiling (perforated gypsum, 200 mm air gap)	A7	9.30	13.44	16.54	13.44	11.37	9.30

ABSORPTION AREA OF THE ROOM: A=A1+A2+A3...

Room with glass wool ceiling
(A = A1+A2+A3+A4+A5+A6+A7)

125	250	500	1000	2000	4000
23.97	27.69	25.95	23.76	25.64	23.53

Room with perforated gypsum ceiling
(A = A1+A2+A3+A4+A5+A6+A8)

125	250	500	1000	2000	4000
22.93	23.56	22.85	19.62	17.37	15.26

REVERBERATION TIME, T=0,161*V/A

Room with glass wool ceiling

125	250	500	1000	2000	4000
0.41	0.35	0.38	0.41	0.38	0.42

Room with perforated gypsum ceiling

125	250	500	1000	2000	4000
0.43	0.42	0.43	0.50	0.56	0.64

Figure B3: The reverberation time calculations of two measured patient rooms. Absorption indices are from (Halme and Seppänen 2002).

C Open plan office: Pictures of the measured spaces

(a) Absorptive wall panel installed on the corridor wall.

(b) From the other end of the corridor.

Figure C1: Measured open plan office. Pictures from both ends of the corridor.

(a) Four-person office room 338.

(b) Absorptive wall panel installed to two-person office room 339.

Figure C2: Measured open plan office. Pictures from office rooms.