Sound quality in Finnish Lutheran churches

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Acoustical measurements were made in twenty churches in the Helsinki area, and their acoustical properties were compared to each other. The churches varied in size from small village churches to large cathedrals, were built between the 1470’s and 2005, and were built of stone, tile or wood. The churches were measured following the ISO 3382 standard. The results showed no clear distinctions between churches of different ages. The average reverberation time was longer than what is recommended for concert halls, with a small correlation to the volume of the church. The results of the modern churches were varying for all measured parameters, with no apparent correlation to the materials, sizes or ages of the churches. The average STI of 0.5 for all measured churches indicates that sound systems are needed in churches for the speech intelligibility to improve in the otherwise reverberant space.

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Preface

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The congregations I visited while measuring the churches deserve a special thank you. The vergers who allowed me inside the churches at varying times of the day and endured my questions about how the church hall was used, and the secretaries who let me dig through their archives in search of architectural drawings: thank you for your help and patience. An extra thank you to the real estate agency at Helsingin seurakuntayhtymä for providing me with excellent drawings of all the churches in Helsinki. I am also indebted to the vicars, cantors and architects who took time out of their schedules to answer my questions.

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Frida Vikström
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Symbols and abbreviations

Symbols

\( \alpha_i \) Absorption ratio of a material
A Absorption area
\( c_{air} \) Sound velocity in air
\( C_{50} \) Clarity
\( C_{80} \) Clarity
\( C_{80,\text{mid}} \) Clarity, mid-frequencies (500 Hz, 1000 Hz)
\( \delta(t) \) Dirac delta function
\( dB \) Decibel
f Frequency
\( h(t) \) Impulse response
I Sound intensity
\( I_0 \) Reference intensity
\( L_I \) Sound intensity level
\( L_p \) Sound pressure level
\( L_{SN} \) Signal-to-noise ratio level
\( L_W \) Sound power level
p Sound pressure
\( p(t) \) Sound pressure
\( p_0 \) Reference sound pressure
P Sound power
\( P_0 \) Reference sound power
\( P_a \) Pascal
Q Directivity of a sound source
\( SN_{\text{app}} \) Apparent signal-to-noise ratio
T Temperature
\( T_{20} \) Reverberation time \([-5 \, \text{dB} - 25 \, \text{dB}] \times 3\]
\( T_{30} \) Reverberation time \([-5 \, \text{dB} - 35 \, \text{dB}] \times 2\]
\( T_{30,\text{mid}} \) Reverberation time, mid-frequencies (500 Hz, 1000 Hz)
\( T_{60} \) Reverberation time
\( T_s \) Centre time
V Volume
\( w_j \) Weight factor for octave bands used in weighted averaging
W Watt
### Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<td>A/D</td>
<td>Analog-to-digital</td>
</tr>
<tr>
<td>BR</td>
<td>Bass ratio</td>
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<tr>
<td>EDT</td>
<td>Early decay time</td>
</tr>
<tr>
<td>IACC</td>
<td>Inter-aural cross-coefficient</td>
</tr>
<tr>
<td>ISO</td>
<td>International Organization for Standardization</td>
</tr>
<tr>
<td>LF</td>
<td>Lateral energy fraction</td>
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<tr>
<td>MAF</td>
<td>Minimum audible field</td>
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<tr>
<td>MLS</td>
<td>Maximum length sequence</td>
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<tr>
<td>MTF</td>
<td>Modulation transfer function</td>
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<td>RASTI</td>
<td>Rapid speech transmission index</td>
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<tr>
<td>RH</td>
<td>Relative humidity</td>
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<tr>
<td>RT</td>
<td>Reverberation time</td>
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<tr>
<td>SFS</td>
<td>Finnish Standards Association</td>
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<tr>
<td>SNR</td>
<td>Signal to noise ratio</td>
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<td>STI</td>
<td>Speech transmission index</td>
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</table>
1 Introduction

When asked to imagine a typical church, most people seem to form a picture of a large, reverberant room with a high ceiling, the very atmosphere of which prompts you to still and quiet down. In a historical context this makes sense: for hundreds of years the Christian church was the largest institution in Europe, and the congregations needed to be able to host all their members for the weekly services. The priest needed to make himself heard to everyone in the room, and without modern sound systems the room itself had to provide the means.

While modern sound systems nowadays can be found in most Finnish churches, the church halls tend to be unfit for many of the events the Lutheran church now offers. While every congregation still celebrates service of worship every Sunday, the number of attendants is dwindling, and the services are perceived as outdated and boring by much of the younger generation. Other types of activities, such as youth nights, discussion groups, and choir practises, tend to be much more popular, but usually the church halls are deemed unfit for such activities. The acoustics of the church halls play a big role in this: if the room echoes too much, trying to keep a discussion going is not going to work. Participants in more modern forms of worship, where electrically amplified instruments and microphones are used, also find church halls hard to work in, since they are not built with amplified music in mind.

Although churches have been a central part of European towns and villages for several hundred years, their acoustics have not been a focus of studies until the late 1990’s and 2000’s. The acoustics of Finnish churches have not been thoroughly investigated, and so this thesis will attempt to dip a toe into a largely untouched subject. While designing concert halls acoustically has been done since the 19th century, public spaces have gone largely untreated up until the 1990’s, at least in Finland. The question of how to specify the sound qualities of a church has not been answered by either acousticians, architects, or priests, even though everyone has a personal opinion of what constitutes good church acoustics. The most common description seems to be that it should sound sacral, but no one has been able to put into words exactly what that means. This thesis will investigate the sound quality in Finnish Lutheran churches in the Helsinki area, including a few who are widely regarded as having good acoustics.

1.1 Thesis formulation

The main goal of this thesis is to measure the reverberation time, clarity, bass ratio and speech transmission index of twelve modern churches, i.e. churches of varying
materials built no earlier than the 1950’s. The results will then be analysed and compared with the goal to find trends and similarities between the churches. Eight older churches, both wooden and stone, will also be measured, and their results compared with the modern churches to see whether any significant changes can be detected. Any differences between churches built in consultation with an acoustician and churches built without one will be paid special attention to. Measurement reports for each church can be found in the appendices.
2 Behaviour of sound and hearing

This chapter describes the basics of sound and human hearing.

2.1 Basic measures

In its most basic form sound is a wave propagating in a medium, in most cases caused by a vibrating object. Undesirable sound is called noise, but even if noise can be disturbing and irritating it carries information that help us orient ourselves in the surrounding environment. In air, sound waves consist of consecutive volumes of compressed and decompressed air, i.e. deviations from the static air pressure. As such, sound pressure is one of the most important physical measures in acoustics. It can be measured very easily, and condenser microphones can transform sound pressure into electric signals with high accuracy. Sound pressure is measured in Pascal [Pa]. [20] [37] The sounds a human can hear appear in approximately the range $2 \cdot 10^{-5} \ldots 50$ Pa [25].

Since sound pressure in Pascal varies over a very large range, it is more convenient to use the logarithmic unit decibel instead. Sound pressure level is calculated as

$$L_p = 20 \log_{10} \left( \frac{p}{p_0} \right) \text{[dB]},$$

(1)

where $p_0 = 20 \cdot 10^{-6}$ Pa is the reference sound pressure, roughly corresponding to the threshold of hearing. Humans can hear sounds in the range 0–130 dB. [26] [37]

Sound power, measured in watts [W], is defined as the physical work done in one second. It is considered to be the property of a sound source radiating energy along with the sound wave. Like sound pressure, sound power is more easily expressed in decibel as the sound power level:

$$L_W = 10 \log_{10} \left( \frac{P}{P_0} \right) \text{[dB]},$$

(2)

where $P$ is the sound power of the source and $P_0 = 1 \cdot 10^{-12}$W is the reference power. [20] [37]

Sound intensity describes the flow of energy and is defined as the sound power through a unit area. Sound intensity level is defined as

$$L_I = 10 \log_{10} \left( \frac{I}{I_0} \right) \text{[dB]},$$

(3)

where $I_0 = 1 \cdot 10^{-12}$W/m$^2$ is the reference intensity. [37]
2.2 Sound waves

Sound waves behave similarly in gases and liquids, and those mediums are usually referred to as fluids. The sound velocity is characteristic for each medium in which sound propagates. For air, the velocity depends on temperature:

\[ c_{\text{air}}(T) = 331.3 + 0.6T \text{[m/s]}, \]  

(4)

where \( T \) is the temperature in °C. This approximation is valid for normal room temperatures. [37]

In practise, a sound field is so complicated that it can not be solved analytically. With some simplifying assumptions, however, it can be approximated numerically and its characteristics understood, in many cases, quite easily. The two simplest approximations are spherical and planar wave fields.

A spherical, vibrating sound source emits a spherical wave field, where the sound pressure in the wave will be inversely proportional to the distance from the mid-point source of the sphere. The size of the sphere does not have an effect on the wave field, though a larger sphere is a more effective radiator. A point source is a useful abstraction, as any sound source that vibrates quite homogeneously, and is small in size compared to the wavelength, can be approximated as one.

Similarly, a large vibrating planar surface emits a plane wave. The planar wave front preserves its waveform in a lossless medium, as can be seen in figure 1, but if the area or any acoustic parameter of the medium change, the wave will be split so that part of it reflects back and part continues to propagate. In a homogeneous tube only a plane wave can propagate at frequencies where the cross-sections of the tube are small in comparison to the wavelength. Practical examples of this include flutes, clarinets and organ pipes. [37] [25]

![Figure 1: Plane wave propagation in a tube.][37]
2.3 Sound field in a room

In a room, the sound will propagate from the source to the receiver along several paths. The first wave front arrives along the direct path (as long as the source is visible to the receiver). Direct sound is followed by early reflections and diffracted components from the walls, floor and ceiling, and then by reverberation, where the individual reflections may not be separately visible or audible. Early reflections increase the loudness of the sound and contribute to spatial perception, while late reverberation can decrease the intelligibility of speech and fast passages in music. [4]

![Figure 2: Path of direct sound and first reflections from speaker to listener in a simple room.](image)

The reflections and room reverberation will have an amplifying effect in a room, and can be understood by considering the summation of direct and reverberant sound. The level of the reverberant field is approximately constant in the room, and thus the total sound pressure level will be

\[ L_p = L_W + 10 \log_{10} \left( \frac{Q}{4\pi r^2} + \frac{4}{A} \right) \text{[dB]}, \]

where \( L_W \) is the sound power level of the source in dB (see equation 2), \( Q \) is the directivity of the source, \( r \) the distance from the source to the receiver in meters, and \( A \) the absorption area of the room surfaces in \( \text{m}^2 \). The directivity is 1 for an omnidirectional source, for other sources it can have larger or smaller values depending on the direction. The first term inside the logarithm corresponds to the intensity caused by direct sound, and the second to the reverberant field. As the sound pressure level depends on the distance \( r \), the direct sound pressure level will decrease by 6 dB for every doubling of the distance. At a certain distance the direct and reverberant fields will have the same level, beyond which the total field remains approximately constant. This distance is called reverberation distance or the radius
of reverberation. [37]

2.4 Hearing

The human auditory system is able to receive and process a wide range of different sounds. The useful range is from about 20 Hz to 20 kHz, although both lower and higher frequencies can be perceived if they are intense enough. The smallest amplitude of a tone that causes an auditory event is called the hearing threshold, and, as alluded to earlier, the sound pressure level scale is defined so that 0 dB is close to the hearing threshold of a pure tone at 1 kHz, which corresponds to the reference pressure $p_0$. Typical speech at a distance of one meter is about 60-70 dB, which is loud enough to produce a good signal-to-noise ratio in most environments. [37] Humans are most sensitive to frequencies between 2 and 5 kHz [18].

Sounds between the threshold of hearing and threshold of pain are perceived with increasing strength, a subjective feature called loudness. The loudness level, measured in phon, has been defined so that the sound pressure level of a 1 kHz pure tone has the same loudness level. In other words, a 50 dB pure 1 kHz tone measures 50 phon on the loudness scale. Based on this, equal loudness curves have been measured and can be seen in figure 3. As can be seen, the loudness curves are dependant on both the frequency and the sound pressure level. [37]

As can be seen, the full range of hearing is quite vast, but in practical communication situations a much smaller area is utilized. For acoustic music the effective range is about the lighter grey area, and for speech the basic range is even smaller. The effective frequency range for acoustical music (around 63 Hz to 8000 Hz) is the most commonly used and analysed frequency range in acoustic measurements, which is relevant also in this thesis. The darker grey area signifies the frequency range for understandable speech communication over a telephone connection.

The human ability to localize sound is surprisingly good. Localization is determined or guided by localization cues, such as interaural time or level differences, which are used to associate direction, distance and other spatial attributes. By utilizing the properties of direct sound, reflections from surfaces and objects, and reverberant sound, the auditory system learns to analyse sound environments. Reflections and reverberations change the binaural cues considerably, which helps for distance perception but can make direction localization harder. [37]
Figure 3: The working range and equal loudness curves of human hearing. The lowest curve specifies the minimum audible field (MAF), the field producing a just audible sound to the subject, as measured in free-field conditions for a sound source in front of the subject. The uppermost curve specifies the approximate threshold of pain. Each separate curve specifies a constant of the perceived loudness for a pure tone. [37]
3 Room acoustics

This chapter describes room acoustic criteria which can be measured to determine the acoustic conditions of a space. These criteria were chosen to provide the greatest potential to describe the acoustical properties of the churches.

3.1 Impulse response

The unit impulse response function $h(t)$ is defined as a system’s response to an ideal impulse, i.e. the Dirac delta function $\delta(t)$. The unit impulse response function perfectly describes a system’s behaviour and response to any input. [26]

In a system such as the one pictured in figure 4, the unit impulse response function will be described as:

$$y(t) = h(t) \quad \text{when} \quad x(t) = \delta(t)$$  \hspace{1cm} (6)

where $t$ is the time that has passed since the moment the delta function was entered into the system. This means that for any system, when the unit impulse response function is known, the system response can be calculated from any input signal using the convolution integral:

$$y(t) = \int_{0}^{\infty} h(\tau)x(t - \tau)d\tau$$  \hspace{1cm} (7)

The lower integration limit is 0, as a physically realizable system cannot produce any output before an input is provided. In most cases the observed system will not be perfectly linear (in a linear system quantities are simply proportional to each other), but even with a small non-linearity present in the system, this method will achieve the best linear approximation for the system. [26]

In room acoustics, the impulse response is a temporal sound pressure function as a result of the room getting excited by a Dirac impulse. Expressed in signal processing terminology, the room is a system of which the impulse response is a property. As it is impossible to create and radiate true Dirac delta functions, impulses that approximate a Dirac impulse are used instead (e.g. a gunshot). An alternative
method is to use a period of maximum-length sequence type signal (MLS) or a sine sweep. [23]

An impulse response measured in an acoustic space provides a good description of the acoustical properties of the room acoustic system. [36] The response between a single source and receiver pair will fully describe the acoustic system between the two locations, but due to sound field variations it is necessary to average data from several measuring points before making any assumptions about the whole space. Figure 5 describes the acoustic system between a source and a receiver in St. John’s church in Helsinki. Measuring room impulse responses is the most common task for an acoustician, since the majority of room acoustic criteria can be calculated from the acoustic impulse response.

Figure 5: Impulse response measured between two points in St. John’s church in Helsinki.

Usually impulse responses are measured with an omnidirectional microphone (a microphone that reacts to sound waves from all incident angles), as it gives all the data needed for the most frequently used parameters. The lateral components of an impulse response, however, need to be recorded with a figure of eight microphone (i.e. a dipole microphone that receives sounds equally from two opposing sides of the microphone and suppresses sound from the other two directions). Lateral energy fractions are calculated using both the impulse response from a figure of eight microphone and the impulse response from an omnidirectional microphone, and they can be used to describe the spaciousness of the room. Spaciousness can also be called spatial impression, and refers to the listener’s feeling of being surrounded, or enveloped, by the sound. Three-dimensional intensity probes and microphone arrays have also been used in attempts to obtain more complete information about the
directivity of the sound and determine directivity patterns, and to describe the sound field even better. As of now, microphone arrays are mostly used in research for improving localization and tracking of sound. Many practical uses of the technology have been proposed, including hearing aids, teleconferencing, acoustic surveillance, and speaker identification.

3.2 Reverberation time

Reverberation time $T_{60}$ is defined as the time it takes for the sound pressure level to decrease 60 dB (which is equal to one millionth) from the original level after a sound source is turned off. In practise, this moment is when the sound becomes inaudible to human ears. This is illustrated in Figure 6.

![Figure 6: Definition of reverberation time. Adopted from [20].](image)

In the beginning of the twentieth century, W.C. Sabine developed a formula based on the relation between reverberation time, the volume, and the absorption area of the room:

$$T_{60} = 0.161 \frac{V}{A}[s]$$  \hspace{1cm} (8)

where the absorption area $A$ is defined as:

$$A = \sum_{i=1}^{n} \alpha_i S_i [m^2]$$  \hspace{1cm} (9)
where $\alpha_i$ are the absorption ratios of the materials in the room, and $S_i$ are the areas of the corresponding materials. Sabine’s formula (equation 8) is in reality accurate only in an ideal diffuse sound field, i.e. a sound field where the sound pressure level emitted by the source is not dependent on position, and thus is constant in every point of the room. Such a sound field can not be achieved even in reverberation chambers, but rooms that are of normal size, open, and contain only a small amount of absorptive materials, can in practise be considered diffuse. [20]

In a diffuse sound field, the decay of the sound field is exponential, and thus linear when plotted on a logarithmic scale. By plotting the impulse response on a logarithmic amplitude scale the reverberation time can be evaluated. In practise the decay curves are not simply exponential, as the exponential decay always is obstructed by background noise at some point, and the decay curve may even bend from one slope to another, resulting in multiple levels of decay [36]. The signal-to-noise ratio (SNR) between the measurement signal and the background noise is rarely the 60 dB as required by Sabine, but as the calculation is based on the assumption of exponential decay, it is not necessary to obtain a full 60 dB of decay. Instead, the calculation of $T_{60}$ can be extrapolated from the part of the impulse response that behaves exponentially.

The value of $T_{60}$ can be found 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. These methods are usually called $T_{30}$ and $T_{20}$ respectively, to distinguish them from $T_{60}$. [26] A similar quantity is the early decay time EDT, which is determined by measuring the decay time between 0 dB and $-10$ dB and multiplying it by six. Ideally, the EDT is equal to $T_{60}$, but the short integration period makes it more vulnerable to errors. [24]

Traditionally the slopes of the decay curves were evaluated manually, either by finding the time difference between predetermined levels (e.g. the aforementioned $-5 \ldots -35$) or by applying a visual "best fit" strategy. As the method depends heavily on the shape of the curve, it can give inaccurate results. [36] [4] A much more elegant solution was presented by Schroeder in 1965. He proposed that the relationship between the ensemble average of all possible individual decay curves and the corresponding impulse response could be expressed as follows:

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

where $y(t)$ are the decay curves and $h(\tau)$ the impulse response [40]. Based on this is the process commonly called backwards integration or Schroeder integration:
where $h$ is a measured impulse response. The integration produces an even decay curve, to which a straight line can be fitted and the reverberation time calculated, as seen in figure 7.

$$L(t) = 10 \log \left( \frac{\int_{0}^{\infty} h^2(\tau)d\tau}{\int_{0}^{\infty} h^2(t)d\tau} \right),$$

(11)

Figure 7: Determining the reverberation time using a fitted line and the root mean square method (lower curve) and using Schroeder integration (upper curve).[26]

As a real impulse response always will contain some background noise, the slope of the decay curve can not be evaluated in its full extent. Reverberation time should therefore be calculated so that the impulse response is truncated 5 dB above the noise floor [23]. In order to separate the reverberations from direct sound and strong early reflections, the first 5 dB should also be excluded from the calculation.

Reverberation time remains the most valuable measurable quantity for room acoustics. [4]

### 3.3 Clarity

Clarity $C$ is defined as the ratio between early and late received sound energy, where the early sound energy is calculated from the first 50 or 80 milliseconds of the impulse response. Clarity is calculated using the following equation:

$$C_{te} = 10 \log \left( \frac{\int_{0}^{t_e} p^2(t)dt}{\int_{t_e}^{\infty} p^2(t)dt} \right)[\text{dB}],$$

(12)
where $t_e$ is the early time limit of 50 ms or 80 ms, and $p(t)$ is the instantaneous sound pressure of the impulse response measured at the measurement point [23]. $C_{50}$ is generally considered to be best suited for determining the clarity of speech, whereas $C_{80}$ is better for determining the clarity of music [36]. Miśkiewicz et al, however, found little actual difference between the two, although subjective auditory judgements indicated otherwise [34]. The higher the value of clarity, the more the early sound dominates, and the sound is subjectively perceived as clear. Accordingly, a low value of clarity indicates an unclear and excessively reverberant sound, and it may be perceived as muddy (a lack of definition in the sound where everything mashes together rather than blends). [39]

3.4 Bass ratio

The bass ratio BR is defined as the ratio of the reverberation times at low frequencies to those at mid-frequencies:

$$BR = \frac{RT_{125Hz} + RT_{250Hz}}{RT_{500Hz} + RT_{1000Hz}},$$

and was proposed by Beranek as a measure of the perception of bass in an occupied concert hall [5]. It is also commonly used as a measure of how warm the tonal colour of a hall is, i.e. a measure of the perception of warmth. [39]

3.5 Speech transmission index

The speech transmission index STI is a criteria describing the clarity of speech transmission in an acoustic space, i.e. a measure of the speech intelligibility between the speaker and the listener, or the percentage of correctly understood syllables. It can vary between 0 and 1, and the higher the value, the better the syllable distinction. When the STI reaches values higher than 0.75 the speech intelligibility in the room is perfect. [20]

STI can be divided into five classes depending on how the speech intelligibility is perceived, as shown in table 1. The middle intervals each correspond to 0.15 on the STI scale, which implies that differences of that magnitude are important and clearly noticeable.

STI can be calculated from an impulse response, by determining the modulation transfer function (MTF) [38]. This method is based on the idea that speech can be regarded as an amplitude-modulated signal, and the speech information is carried in the degree of modulation. Thus, if noise or reverberation was added to the signal.
Table 1: Subjective meanings of STI values. [41]

<table>
<thead>
<tr>
<th>STI range</th>
<th>Speech intelligibility</th>
<th>Examples of spaces</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 0.30</td>
<td>Useless</td>
<td>An old church</td>
</tr>
<tr>
<td>0.30 ... 0.45</td>
<td>Bad</td>
<td>Reverberating auditorium or concert hall</td>
</tr>
<tr>
<td>0.45 ... 0.60</td>
<td>Tolerable</td>
<td>Well planned large auditorium</td>
</tr>
<tr>
<td>0.60 ... 0.75</td>
<td>Good</td>
<td>Well planned classroom or small auditorium</td>
</tr>
<tr>
<td>&gt; 0.75</td>
<td>Excellent</td>
<td></td>
</tr>
</tbody>
</table>

during the transmission path, the degree of modulation would be reduced, which would result in reduced intelligibility. [39]

To calculate the STI, the MTF needs to be determined for 98 data points. These are obtained for seven octave bands with centre frequencies 125, 250, 500, 1000, 2000, 4000, and 8000 Hz and 14 modulation frequencies spaced a third octave apart: 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 12.5 Hz. The octave bands represent the typical frequency band of normal speech, and the modulation frequencies represent the temporal variations in normal speech [21]. These data points, the so called m-values of the MTF, can be calculated as follows:

\[ m(F, f) = \frac{1}{\sqrt{1 + (T(f)2\pi F/13.8)^2}} \cdot \frac{1}{1 + 10^{-\frac{L_{SN}(f)}{10}}}, \]  

(14)

where \( F \) is a modulation frequency, \( f \) is a frequency band, \( T(f) \) the early decay time of that frequency band, and \( L_{SN} \) the signal-to-noise ratio of that frequency band, determined by subtracting the level of the noise \( L_N \) from the level of the signal \( L_S \).\[20\][21] Having obtained the 98 m-values, their apparent signal-to-noise ratio is calculated:

\[ SN_{app} = 10\log \frac{m}{1 - m}. \]  

(15)

The values of \( SN_{app} \) are limited to the range ±15 dB, and therefore \( SN_{app} = 15 \) dB if \( SN_{app} > 15 \) dB, and \( SN_{app} = -15 \) dB if \( SN_{app} < -15 \) dB. \[22\]

The mean \( SN_{app} \) value for each octave band should now be calculated by simply averaging the 14 values (one for each modulation frequency). The overall mean \( SN_{app} \) is then calculated from the seven octave band means by performing a weighted averaging, which means that some values are given more value, or weight, than others. Each octave band (125, 250, 500, 1000, 2000, 4000, and 8000 Hz) is multiplied by a weight factor as follows: 0.13, 0.14, 0.11, 0.12, 0.19, 0.17, and 0.14. After performing the weighted averaging, the STI is calculated by adding 15 to the overall mean and
dividing the result by 30. This can all be expressed by the following equation:

\[ STI = \frac{1}{30} \left\{ 15 + \sum_{j=1}^{7} w_j \cdot \left( \frac{1}{14} \sum_{i=1}^{14} SN_{app}(F_i, f_j) \right) \right\}, \quad (16) \]

where \( SN_{app}(F_i, f_j) \) are the m-values for each frequency band and modulation frequency, and \( w_j \) is the weight factor for each octave band.
4 Earlier studies

This chapter reviews some previous studies of church and concert hall acoustics.

4.1 Acoustics of concert halls in Finland

While the acoustics of churches in Finland have not been studied previously, Finnish concert halls have been the subject of some studies. Beranek conducted enormous research by gathering both subjective opinions and objective data for several concert halls worldwide, and has been able to rank them according to this data [5] [19]. This inspired much of future research, and questionnaires have been used to evaluate concert hall acoustics in studies by e.g. Barron [3] and Miśkiewicz et al [34].

The research of Finnish concert hall acoustics have largely focused on the perception of acoustics, sensory evaluations, and ways to improve both measurements with and the recording of a loudspeaker orchestra. Lokki and Päätynen found that lateral reflections in concert halls largely contribute to the perception of distance, a fact that has been well known in psychoacoustics but not in architectural acoustics [29]. That knowledge can be beneficial when designing the acoustics of future concert halls, and is a valid factor to take into account when considering the acoustics of churches as well. In a similar vein, when analysing objective, subjective and preference data from assessors, Lokki et al. found that the main attributes discriminating the examined halls were loudness, envelopment (the feeling of being surrounded by the music) and reverberance, while the main preference driver was attributes interpreted as proximity [30]. This indicates that these are attributes worth paying extra attention to. It is interesting that the same study found that the subjective proximity was the attribute that correlated best with the average preference rating, and none of the objective parameters could explain this correlation.

Perhaps most interesting for this thesis is a study made by Lokki et al. that evaluated three concert halls by having assessors listening to sound recorded in different positions in the halls (the sound being anechoic music emitted by a loudspeaker orchestra). The assessors got to develop their own set of attributes, and once they were analysed it appeared that the individually applied attributes agreed very well. [28] This suggests that people tend to focus on similar things when evaluating acoustics, a very interesting point for church acoustics as well. Lokki et al. also found that the perception of reverberance was related either to the size of the space or to the enveloping reverberance, depending on the assessors, something that is highly relevant for church halls.
4.2 Acoustics of churches

Since there are no standards describing how to measure church acoustics, most studies have followed the ISO 3382 standard for concert hall acoustics. Addressing this problem, Martellotta et al. developed a set of guidelines for acoustical measurements in churches, hoping to make comparisons of acoustic characteristics of different worship buildings easier. In a similar vein, Berardi developed a double synthetic index to evaluate the acoustics of churches. This index was defined to synthesize the acoustical properties related to music and speech separately. It combines the average of seven acoustical parameters (EDT, BR, centre time $T_s$, sound strength $G$, inter-aural cross-coefficient IACC, lateral energy fraction LF, and clarity $C_{50}$) and a music or speech index. The index was tested by comparing its values with subjective preferences gathered through listening tests, and showed good adherence with them. Berardi hoped this index would be useful as an instrument to show the acoustical properties of a church to people with low knowledge in acoustics, and the first applications of it showed it to be very capable of representing listeners’ preferences.

Desarnaulds and Carvalho made a very valuable study analysing how architectural style impacts the reverberation time in churches, by measuring 400 churches in 9 countries. While they found that the relationship between RT and volume was not powerful, they did find a small variation in average RT depending on architectural style. In an earlier study, Carvalho, Morgado and Henrique had confirmed that RT can be a reasonable predictor of the subjective feeling of reverberance, and in his dissertation Carvalho stated that RT is the single most significant measure to characterize a church, as it is for concert halls. He also found that a significant difference that happened in acoustical measures could be traced to the reformation and the changes that occurred in the church during that period of time.

Investigating the speech intelligibility of 41 Roman catholic Portuguese churches, Carvalho found that the majority of the tested churches had a rapid speech transmission index (RASTI) below 0.45, giving them a poor rating in the quality of speech intelligibility. An interesting note was that there was a clear improvement in speech intelligibility for churches built in the baroque style (17th-18th century), while the renaissance churches had the lowest values. These values agree with those found by Desarnaulds, Carvalho and Monay when investigating the influence of occupancy on church acoustics. They found the mean STI of an unoccupied church hall to be 0.411 when used acoustically, and 0.492 when a sound system was used. This difference mainly relates to the reduction of the room reverberation time when a sound system is used. On average, the speech intelligibility of an occupied hall
increased with 0.05 compared to the unoccupied hall with the use of an sound system, and with 0.035 without a sound system. [16]
5 Perceived acoustics of churches

Churches have a reputation for being large, reverberant spaces where silence reigns. This might stem from the fact that the most popular churches for tourism are the large cathedrals, where the reverberant environment may hush the visitor into reverential silence [31]. Vicar Stefan Forsén is of the opinion that the reverberant space very much relates to what people have wanted their church to be: in the past, the important thing was that you heard what was being said, while it nowadays is equally important to see what is happening. He believes that the 'feeling of a church' is something people seek intuitively in such a space. [17] Vicar Helene Liljeström agrees, and adds that she herself often experiences something of a heavenly dimension in churches, something that’s not as easily found in ordinary rooms. [27]

5.1 Architecture and function

The fact that people have a somewhat stereotypical view of what a church should look like also directly impacts the acoustics of the space. Martti Simojoki writes that "a church will look like a church even when it does not follow traditional style trends" [43] but as Blauert writes 'even unconventional designs must still show the typical perceptual features, otherwise, for instance, a concert hall would not be accepted as a concert hall any more" [8]. This later view has been prevalent for many different culturally significant buildings, and cantor Dag-Ulrik Almqvist believes that architects and interior designers still resort to stereotypical and old-fashioned solutions when designing a church hall [1]. This results in the acoustics of the space not being optimized for the actual use, but for an arbitrary idea of what the church hall is used for. Cantor and organ teacher Markus Malmgren gives the Turku cathedral as a good example of the problems with the perception of church acoustics: the cathedral technically has magnificent church acoustics, he says, but is very unwieldy musically, and hard to perform in with larger ensembles [32].

Vicar Johan Westerlund ponders that architects maybe don’t generally follow the development within the church and as such are out of touch with the current trends in congregations [44]. Vicar Daniel Björk continues this train of thought and ponders that architects maybe seldom are active churchgoers themselves, don’t have the active engagement that would keep them on top of how a congregation functions today. Thus they usually design a space better suited for an earlier generation [7]. Malmgren elaborates that the functional post-world war two architecture in Finland in general has affected church architecture in a way that seldom prioritizes acoustic properties. He adds that church halls usually are problematic since their ceilings are
so high relative to how wide and long the rooms are. Here architect Simo Paavilainen agrees, adding that this usually results in a too long reverberation time. From an acoustic point of view, Malmgren thinks that it would be preferable for a church to have simple and 'architecturally boring' proportions. The interior design could then give the room the dignity and reverence it needs. Paavilainen is of the opinion that a skilled acoustician always is needed when designing a church, to make sure that the acoustics will be optimal for the room.

In the future, Björk believes, church halls might be so called multifunctional rooms that are more adapted to speech and electrically amplified music, adding that to him the most important quality is that the room is flexible enough to be used for many different kind of events. Malmgren on the other hand remarks that multifunctional rooms are problematic since they are not optimized for any of the functions the room is used for. Neither speech nor music generally benefits from the acoustics being manipulated in a way that makes it unpredictable. Malmgren also adds that solutions where the church hall can be enlarged by opening the wall to the congregation hall seldom works well acoustically. Paavilainen, however, agrees with Björk, also offering the opinion that the church rooms of the future likely will be smaller than the average today.
5.2 Music and speech

Although the reformation put a stronger emphasis on "the word" and thus laid the groundwork for the necessity of high speech intelligibility [31], liturgical music and community singing has traditionally been an important part of the mass in Finnish churches. Westerlund strongly believes that a church hall needs to be good for community singing, and that this should be the main focus when designing the acoustics of such a space. He believes that speech intelligibility then can be solved with a proper sound system. Almqvist agrees, and adds that good church acoustics makes it easy to sing and feel that you have a connection to the rest of the congregation, whether you sit in the pews or on the balcony. Malmgren emphasizes the importance of community singing, and that church music above all other kinds needs to be inclusive and not exclusive. Electrically amplified music can never be as inclusive, he believes, and too easily divides the congregation into listeners and performers. He adds that church rooms can not be planned for both acoustical and electronically amplified music. Especially bigger rooms should always be planned for only one or the other, and he thinks we should accept that some rooms work better for one kind of music, and other rooms for other kinds.

Forsén offers another point of view and says that the acoustics of a church ideally would allow the speaker to talk as naturally as possible, and that the listeners would feel like the speaker speaks directly to them. If the speaker has to talk in a specific manner to be heard properly, whether with a sound system or without, a lot of the naturalness disappears, he believes. Both Forsén and Björk point out that the most common response from the congregation is how well they could or could not hear what the preacher said during mass.

Malmgren notes that speech and music always will contrast in some way, but that organ music will come into its own much better in more reverberant rooms. The speakers and musicians should also be able to adapt themselves to the acoustic realities of the room. Westerlund adds that if a room is too ‘dry’ (i.e. has a short reverberation), it is perceived as a bigger problem than if the room is too reverberant. Malmgren thinks that if the organ music sounds good, the room is probably well suited for worship, but emphasizes that this does not mean that the reverberation time should be as long as possible.

5.3 Sound systems

Sound systems are almost universally used in Finnish churches today, and all four vicars say that they prefer to conduct mass with a sound system, rather than without.
All of them also agree, however, that the sound systems in churches seldom are optimized for the church hall in question. Björk says that there is too much distance between the people who order and pay for the system, and the ones who actually have to use it. His experience is that the church caretakers usually do not have the required knowledge to properly utilize the sound systems, and that there exists a certain fear of technology. In most churches he works in, the audio mixing console is locked away and not to be touched, instead of using it to ensure every event has the best possible sound reproduction. In his opinion it is absurd that so much money is being put into systems that are not used to their full capacity.

Malmgren agrees, saying that the AV-systems in churches usually are unnecessarily expensive and impractical. Usually the people who order the systems do not have good knowledge of how sound systems work and what properties you should expect from them. Westerlund also adds that the use of churches has changed a lot in a relatively short amount of time, and that it pains him when a sound system can’t be placed as is best from an acoustic point of view, but instead has to yield to what is deemed best visually.
6 Measurement and methods

This chapter describes the used measurement devices and software as well as the measurement techniques. The measured churches are also described.

6.1 Devices and program

The measurements were carried out following the requirements of the ISO 3382-1 standard. A logarithmic sine sweep was used as stimulus, generated by the ARTA software on a HP Envy 14 notebook PC, and transmitted to the church using a dodecahedron loudspeaker (figure 9), via a Hypex UcD400 pre-amplifier (seen in figure 10). A Roland OCTA-CAPTURE sound card (seen in figure 10) was used as an A/D converter, and a B&K 4006 omnidirectional microphone (seen in figure 10) as a receiver. The temperature and relative humidity of the air were measured using a Tinytag View 2 TV-4505 data logger (figure 11). The ARTA software was also used to record the measurement signal, and for calculating the reverberation time, the clarity, the bass ratio, and the MTF from the measured impulse responses. The speech transmission indexes were calculated in Microsoft Excel, using the m-values provided by the MTF. All measurement values were averaged as per the aforementioned standard, and the results are presented in the format required by it.

Figure 9: The loudspeaker used in the measurements.
Figure 10: The Hypex UcD400 amplifier, Roland OCTA-CAPTURE sound card, and B&K 4006 microphone used in the measurements.

Figure 11: The Tinytag data logger used in the measurements.
6.2 Setup

As there is no standard for measuring the acoustics of churches, the closest match is to treat the room as a performance space as per the ISO 3382-1 standard. It requires the sound sources to be located where the natural sound sources of the room would be, and the receiver positions to be representative of where listeners would normally be, which is how the measurement positions for this thesis were chosen [23]. The measurements done for this thesis followed the standard in reference to the height and placement of the sources and receivers, the amount of source-receiver pairs, and the way the data was collected.

The altar and the organ were two obvious locations for sound sources, as both are integral in any Lutheran mass. The lectern and the pulpit were two other possible locations, but as both are used for speech only it was deemed unnecessary to use both locations, especially since only one of them is used regularly in many churches. As pointed out by Martellotta et al. churches are often used for other kinds of musical performances, which usually take place in front of the altar [33]. Thus it was decided to use four source locations for each measurement: S1 behind the altar, where the priest stands most of the time, S2 behind the lectern or the pulpit, depending on which one the congregation reported was used more, S3 in front of the altar, at the end of the aisle, where a choir or group of musicians would perform, and S4 by the organ. The fourth source location is the one that varies the most between the churches, as the location of the organ in the church is not as regular as the location of the altar. The sources were all placed at a height of 1.5 m.

The receiver locations were chosen based on each individual church so that the "audience" area was covered as well as possible. Due to the varying size and form of the churches, the amount of receivers varied between six and ten, as required by the ISO 3382-1. All receivers were placed at a height of 1.2 m. The individual receiver positions can be seen in figures 12 through 31 and as larger images in the appendices.

The churches were all measured while unoccupied, as getting a congregation of the same size to be present in every church would have proven difficult. In addition, most of the available bibliography has data based on measurements conducted in unoccupied conditions.

6.3 Measured churches

20 churches built between the 1400’s and 2005 were measured. The churches were chosen based on age, building material, and architectural style, so as to give a wide variety of data. For practical reasons the churches are all located in or close to
Helsinki. As seen in table 2, most are modern churches built in the 1950’s or later with a handful of older churches as reference points. Of the measured churches, all except Pohja church have been built after the reformation, i.e. they have all been built as Lutheran churches, while Pohja church was built for a catholic congregation. The main material used gives an interesting insight in the preferred building material at the time.

Table 2: List of all measured churches.

<table>
<thead>
<tr>
<th>Name of the church</th>
<th>Year built</th>
<th>Main material</th>
<th>Amount of seats</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pohja church</td>
<td>1470’s</td>
<td>Stone</td>
<td>350</td>
</tr>
<tr>
<td>Tuusula church</td>
<td>1734</td>
<td>Wood</td>
<td>480</td>
</tr>
<tr>
<td>Lapinjärvi church</td>
<td>1744</td>
<td>Wood</td>
<td>450</td>
</tr>
<tr>
<td>Karjalohja church</td>
<td>1860</td>
<td>Stone</td>
<td>420</td>
</tr>
<tr>
<td>St. John’s church</td>
<td>1891</td>
<td>Tile</td>
<td>2600</td>
</tr>
<tr>
<td>Kallio church</td>
<td>1912</td>
<td>Stone</td>
<td>1100</td>
</tr>
<tr>
<td>St. Paul’s church</td>
<td>1931</td>
<td>Tile</td>
<td>800</td>
</tr>
<tr>
<td>Kulosaari church</td>
<td>1935</td>
<td>Concrete</td>
<td>170</td>
</tr>
<tr>
<td>Munkkiniemi church</td>
<td>1954</td>
<td>Concrete</td>
<td>450</td>
</tr>
<tr>
<td>Kannelmäki church</td>
<td>1968</td>
<td>Concrete</td>
<td>504</td>
</tr>
<tr>
<td>Temppeliaukio church</td>
<td>1969</td>
<td>Stone</td>
<td>750</td>
</tr>
<tr>
<td>Roihuvuori church</td>
<td>1970</td>
<td>Tile</td>
<td>450</td>
</tr>
<tr>
<td>Oulunkylä church</td>
<td>1972</td>
<td>Tile</td>
<td>250</td>
</tr>
<tr>
<td>Myyrmäki church</td>
<td>1984</td>
<td>Tile</td>
<td>450</td>
</tr>
<tr>
<td>St. Matthew’s church</td>
<td>1985</td>
<td>Tile</td>
<td>200</td>
</tr>
<tr>
<td>Myllypuro church</td>
<td>1992</td>
<td>Concrete</td>
<td>150</td>
</tr>
<tr>
<td>Masala church</td>
<td>2000</td>
<td>Concrete</td>
<td>90</td>
</tr>
<tr>
<td>Church of the Good Shepherd</td>
<td>2002</td>
<td>Tile</td>
<td>350</td>
</tr>
<tr>
<td>Laajasalo church</td>
<td>2003</td>
<td>Wood</td>
<td>350</td>
</tr>
<tr>
<td>Viikki church</td>
<td>2005</td>
<td>Wood</td>
<td>200</td>
</tr>
</tbody>
</table>

The following part consists of short descriptions of the measured churches, including their surrounding environment.

Pohja church. Built in the 1470’s, this granite church is located in the small town Pohja in southwestern Finland, close to one of the main roads. There is limited traffic around it and the area is very quiet. The church has two naves, the northern one narrower than the southern, and three massive pillars obscure the view on the northern side of the church. At the back of the church there is a balcony, and the organ is placed in the front, near the altar. The walls, floor, and ceiling are all made of stone, the pews of wood. The church can seat ca 350 visitors.
Tuusula church. This wooden, cruciform church built in 1734 can be found in the municipality of Tuusula north of Helsinki. It is located outside the current city centre and the area receives only limited traffic. It seats 480 people and has balconies in three of its wings, the fourth hosting the altar. The organ is located on the balcony opposite of the altar. The walls, ceiling, floor and pews are all made of wood, with mats covering the aisles.

Lapinjärvi church. Very similar to Tuusula church, Lapinjärvi church was built in 1744, is cruciform and made of wood. It is located in the centre of the rural Lapinjärvi municipality, and most of the traffic to the village will pass by the church. 450 people can be seated in the church. Like Tuusula church, Lapinjärvi church has balconies in three of the wings, although Lapinjärvi’s are slightly longer, and here too the organ is situated on the balcony facing the altar. The floor, ceiling, walls, and pews are all made of wood, with mats covering the aisles. The pews are positioned closer to each other, leaving less leg room, than the ones in Tuusula.
Karjalohja church. This large stone church built in 1860 fell into disrepair after a fire in 1970, and was restored as recently as 1990. It is located in the rural Karjalohja village west of Helsinki, right by the main road through the village. The church is large and rectangular with bare granite walls, large windows, a stone floor, and a high, wooden ceiling. The pews are made of wood and can fit 420 visitors. There is a lot of space between the front seats and the altar, and the church’s digital organ is situated there.

St. John’s church. Located in the southern part of the centre of Helsinki, this tile Gothic cathedral was built in 1891. It stands right by a road with lively traffic, but is surrounded on two sides by a park, and high buildings on another. The church seats 2600 people and is a popular concert venue. It has three naves, with balconies stretching along both side naves, and along the back wall of the church, where the organ is found. The floor, walls, balconies, and ceiling are made of stone, and the pews of wood. The altar is placed in front of a high altarpiece of wood, and several
tall windows adorn the walls.

![Figure 16: Floor plan of St. John’s church.](image1)

**Kallio church.** This large 1912 church is built in romantic nationalism style, said to be inspired by the dimensions of Solomon’s temple. It is found at the top of a hill in the Kallio district of Helsinki, close to the city centre. The roads closest to it have only limited traffic, but only a short bit down the hill are roads frequented by trams and buses. The church is divided into three naves, with balconies covering the side ones, and it seats 1100 people on its wooden pews. The organ is located on the balcony at the back of the church, and the altar stands in a chancel with high windows. The floor, high ceiling, balconies, and walls are all made of stone.

![Figure 17: Floor plan of Kallio church.](image2)

**St. Paul’s church.** This large tile church was built in 1931 right by what is now one of the busiest roads in and out of Helsinki. It seats 800 people, and pillars delimit two narrow aisles on either side of the church. The floor, walls, and high ceiling are all made of stone, and the pews of painted wood. The organ is situated
on a balcony at the back of the church, and the altar in an elevated chancel at the front. High windows ornate the walls.

![Figure 18: Floor plan of St. Paul’s church.](image)

**Kulosaari church.** Completed in 1935, this small stone church stands on a hill surrounded by nature, a couple of hundred meters away from the closest road. The floor is made of tile, the ceiling of wood, and the walls of stone, and the wooden pews seat 170 people. The organ can be found on the balcony at the back of the church, and the altar stands in an elevated chancel. Three windows adorn the southern wall.

![Figure 19: Floor plan of Kulosaari church.](image)

**Munkkiniemi church.** Completed in 1954, this is the oldest of the modern churches in this thesis. It is found in western Helsinki, at a quiet street some hundred meters away from the nearest tram line. Unusually for a church, the floor slants downwards so that the altar is at the lowest point. The wide, wooden pews seat 450 people, and the organ is situated in the front, beside the altar. The floor is made of stone, the walls of tile, and the roof of plaster.
Kannelmäki church. This concrete church built in 1968 can be found in northern Helsinki, by a road with limited traffic. It is meant to resemble the tabernacle, the shrine tent used by the Israelites, so the church is square-formed, but the four hyperbolic paraboloidal surfaces of the roof rise up sharply to a point 24 meters over the middle of the church. The roof and walls are made of concrete, and the floor of stone, with a mat covering the aisle. The wooden pews can seat 504 people, and the organ can be found in the front of the church.

Temppeliaukio church. Also known as the Rock church, it was completed in 1969 and is a very popular concert venue. It is found in the centre of Helsinki, surrounded by high buildings, and quite close to heavily trafficked roads. The church is excavated directly into solid rock and covered by a dome lined with copper. The floor is concrete, but the walls consist of the uneven, bare rock the church was carved into. The wooden pews seat 750 people, and the organ is placed on the left side of the church. At the back of the church there is a balcony.
Roihuvuori church. Built in 1970, this large, hexagonal tile church stands at in a somewhat busy junction in eastern Helsinki. The floor is made of stone, the walls bare tile, and the high ceiling bare concrete, with beams forming a star of David. The wooden pews can seat 450 people, and the organ is found in the front right of the church.

Oulunkylä church. This small brown brick church was completed in 1972. It is found in northeastern Helsinki beside a road frequented by buses. Its floor is made of tile, the ceiling of concrete, and the walls of tile, concrete, and windows to the upper floor that are often covered by blinds. The metal chairs are not fixed to the floor and can seat 250 people. The organ is found in the middle of the left side of the church.
Myyrmäki church. Completed in 1984, this church has been called the Church of Light. It is located in Vantaa north of Helsinki, right beside the railway tracks and a busy road. It can seat 450 people in its wooden pews. The floor is made of tile, and the ceiling and the walls of concrete and wood. Windows of varying sizes can be found on all walls, and several textiles hang from the ceiling and on the wall behind the altar. The ceiling is lower at the back of the church. The organ is found on the left side of the church. The acoustics for this church were planned.

St. Matthew’s church. This tile church was finished in 1985, and can be found right beside the largest shopping centre in the Nordics and the Stoa cultural centre. Accordingly, there is usually heavy traffic around the church. All surfaces inside the church are made of tile and brick, and the movable chairs made of wood and straw can seat 200 people. The organ is situated on the right wall.
Myllypuro church. Surrounded by several apartment complexes and walking paths in eastern Helsinki, this small church was built in 1992. The floor is made of tile, the ceiling of concrete, and the walls of concrete covered with several wooden panels. The left wall is made completely of wood. Half of the upper part of the back wall consists of three large windows, while several small windows are scattered on the right side and front walls. The organ is placed on the right side of the church, and a small balcony stretches along part of the back wall. The removable chairs can seat 150 people.

Masala church. This small church was built in 2000 in the Kirkkonummi municipality west of Helsinki. It is located close to the centre of Masala village, but receives very little traffic. The floor is made of tile, and the ceiling and walls of concrete. The organ is placed in the front of the church, and the removable chairs can seat 90 people.
Church of the Good Shepherd. This church hall was added to the church in 2002, at the same time converting the old church hall into the parish meeting hall. It is located in northern Helsinki right by the busiest highway in Finland. The floor is made of tile, and the walls and ceiling of concrete. At the back of the church there is a balcony, whose front is made of wood. The organ is located at the front of the church, and the removable wooden chairs can seat 350 people. The acoustics for this church were planned.

Laajasalo church. This wooden church was built in 2003 and has since won prizes for its architecture and use of materials. Located close to a shopping centre on an island in southeastern Helsinki, several bus lines have a stop beside it. The whole interior is made of wood, except the removable metal chairs that can seat 350 people. The organ is located on the left side of the church, and part of the right wall consists large windows. The acoustics for this church were planned.
Viikki church. Built in 2005, this wooden church is found among apartment complexes north of Helsinki city centre, with little traffic around it other than individuals driving home. The whole interior is made of wood, including the removable chairs, and the church can seat 200 people. The organ is located on the right side of the church, and in the back of it the ceiling is much lower. Large windows adorn the left wall of the church.
7 Results

This chapter discusses the measurement results as a group. For individual results, refer to the appendices.

7.1 Reverberation time

The average mid-frequency reverberation time of the churches can be seen in figure 32. Generally, good concert halls have a mid-frequency reverberation time between 1.8 and 2.2 seconds, and the SFS 5907 calls for auditoriums to have a reverberation time between 0.6 and 0.9 seconds [41]. As a church is neither an auditorium nor a concert hall, it is hard to pinpoint what a good reverberation time would be. The balance between speech and music also makes it hard to root for a value in either side of the spectrum: a church hall optimized for speech will probably be too dry for organ accompanied music, while a very reverberant church hall will suffer from bad speech intelligibility.

![Mid-frequency reverberation time in all measured churches](image)

Figure 32: Average reverberation times for the measured churches.

From figure 32 we can see that the majority of the churches have a reverberation time between 1.5 and 3 seconds, the average RT for all measured churches being 2.35 s. This falls a bit above the recommended RT for concert halls and way beyond what is considered good for a room where speech is prioritized. Though the vicars and cantors all agreed that music is a very central part of the mass (as discussed in chapter 5), a reverberation time that high might seem excessive. However, in a larger room, a longer RT is more acceptable, as the time it takes for the sound to
properly 'fill out' the room will be longer. As such, a longer RT is more optimal for a large church than a small one.

It is interesting to see that the two wooden churches built in the 18th century have the shortest reverberation times out of all the measured churches. That both are relatively small and, more importantly, that the interior is made almost completely of wood probably plays a big role in this result. The modern, quite small, wooden Viikki church can also be found in the lower end of the results, adding to this hypothesis. Laajasalo church, however, which also is a modern church made of wood, albeit quite large, sports a reverberation time of 2.3 seconds, a second longer than the old churches in Tuusula and Lapinjärvi. On the other end of the spectrum we can find the large early 20th century cathedrals St. Paul and Kallio, both sporting an RT over 3.5 seconds. In fact all five churches whose RT is over 2.5 seconds are large and with an interior made of stone, tile or concrete, all very hard and non-absorbing materials. They are, however, built at very different times: two in the 1800’s, two at the beginning of the 20th century, and one in 1970. Overall, it is hard to see any clear correlation between the age of a church and its reverberation time, as figure 33 illustrates, or between the reverberation time and the material of the church, as figure 34 illustrates.

![Reverberation time vs. year built](image)

Figure 33: Reverberation time of the measured churches and the years they were built.

It would be tempting to draw conclusions about the apparent correlation between volume and reverberation time that Desarnaulds and Carvalho describe [15], but the data analysed here does not give us enough information about the volumes of the churches. Figure 35 shows both the reverberation time and the amount of seats in each church, but as there are no standard church measurements, the data does not tell us very much about the actual sizes of the churches.
Figure 34: The main material of the churches and their reverberation times.

Figure 35: Reverberation time and amount of seats in each church.

An interesting note is that Temppeliaukio church, which is a very popular church for concerts, has a reverberation time of 2.08 seconds, which falls very neatly into the interval of good reverberation times for concert halls.

7.2 Clarity $C_{80}$

Figure 36 describes the clarity of the measured churches. The desired values for concert halls are usually between -1 and -5 dB [5] (although an interval of -2 ... 2 dB has also been proposed [4]), which of course correlates strongly (but inversely) with the desired reverberation time interval. A hall with high values of clarity usually has a shorter reverberation time, and can therefore be perceived as too dry even if the sound comes through very clear. A very reverberant space makes for a more blended
sound, as several reverberations converge, but a certain degree of blending is desired when music is concerned. The average clarity for all measured churches was -1.91 dB.

### Mid-frequency clarity for all measured churches

![Figure 36: Average clarity for all measured churches.](image)

It is no surprise to see that the same five big churches that had the longest reverberation times also have the lowest values of clarity. Now they are joined by Pohja church, however, which places all the measured old stone churches in the lower end of the spectrum. The old wood churches Lapinjärvi and Tuusula can be found in the opposite end, with Tuusula reaching a value of 0.75 dB, indicating that the sound in that church is perceived as clear. However, due to the church’s relatively short reverberation time, the sound in it may feel dry.

There is a clear jump between the clarity of the big stone churches and the smaller, modern ones. Most modern churches have clarity values between -0.4 and -2 dB, the exceptions being the aforementioned Roihuvuori with its -3.75 dB, and Viikki and Temppeliaukio that both reach positive values. Among the modern churches there is no clear order in reference to either age, material or size, though. Viikki’s 0.09 dB indicates that the early sound energy in the room is almost equal to the reverberant energy. The small positive value of 0.23 dB may have impacted Temppeliaukio church’s popularity as a concert venue: the space is reverberant (as discussed in section 7.1), but the sound still likely perceived as clear rather than muddy (the sounds do not overlap and drown each other out), which is what might happen in the reverberant churches with low values of clarity.
7.3 Bass ratio

The average bass ratio for all measured churches was 0.92. As can be seen in figure 37, the results are a bit more consistent here, with the majority of the measured churches having a bass ratio close to 0.8. St. Paul’s church once again stands out in the high end with its BR of 1.47 but the otherwise there are few parallels to the previous measurements. St. John’s church, that had both a long reverberation time and a large negative clarity value just like St. Paul, can now be found in the opposite end of the spectrum with a BR of 0.76. The other old stone churches are spread out over the spectrum: Karjalohja shares St. John’s BR of 0.76 and Kallio nears St. Paul with a BR of 1.1, but Pohja is found in the middle with a BR of 0.85. This is a clear deviation from the reverberation times and clarity values of the same churches, which were all quite close to one other. The early 1900’s, quite small, stone Kulosaari church stands out in the lower end of the spectrum with a BR of 0.62.

![Bass ratio for all measured churches](image)

Figure 37: Average bass ratio for all measured churches.

The bass ratios of the modern churches are very similar, the exceptions being Munkkiniemi, Laajasalo, and Kannelmäki that all have a BR over 1. While Laajasalo and Kannelmäki both have high ceilings, Munkkiniemi is a quite small church with normal room ceiling height, so it’s hard to see any similarities between them. Laajasalo is also made of wood while Kannelmäki has mostly bare concrete as its interior. The wooden churches overall have very differing results here: Tuusula is in the lower end with a BR of 0.73, while the very similar Lapinjärvi has climbed higher to 0.92. Laajasalo, as mentioned, is found in the higher end with 1.17, and Viikki resides in the very middle with 0.89.
A study by Hidaka and Beranek concludes that the bass ratio should be larger than 1.05 in opera houses [19], significantly higher than the BR of most of the measured churches. It is important to notice that this conclusion was made based on measurements in occupied halls, though, while the measurements for this thesis were made in unoccupied spaces. Carvalho measured 41 Portuguese churches in unoccupied states in a dissertation, and found that the mean BR for those churches was 0.98, not very far from the mean BR of 0.92 this thesis found. Carvalho also discovered that the bass ratios could not be well predicted by examining a set of architectural parameters, a pattern that is also seen in these results. [11]

### 7.4 Speech transmission index

The speech transmission index is perhaps the easiest of these room acoustic parameters to quantify, as the SFS standard has divided the index neatly into classes based on quality, as seen in table 1. The average STI for the measured churches was 0.5 which falls into the "tolerable" class, not bad but not good either. In fact, none of the measured churches have an STI that would be classified as good. As can be seen in figure 38, the old wooden churches Tuusula and Lapinjärvi can once again be found in the high end with the speech transmission indexes of 0.59 and 0.56 respectively, and are joined at the top by the early 20th century stone Kulosaari church with its STI of 0.58. These three churches come closest to having a good STI, as some of their individual measurement points reached values over 0.6 even if the average is not as high.

![Speech transmission index for all measured churches](image-url)
St. Paul’s church stands out, once again, as the only church that is classified as having bad STI with its value of 0.38. Its excessive reverberation time probably plays a big part in the low STI, as the late reverberations will disturb the direct sound, and thus lower the speech intelligibility. This low STI indicates that speech can be very hard to understand in St. Paul’s church, even with a sound system, something no preacher should want to experience.

The other four old stone churches that had long reverberation times and low values of clarity can also be found in the lower end of the STI results. Kallio, St. John, Karjalohja and Pohja all barely make it over the 0.4 limit into the tolerable territory, but the low values does not bode well for the speech intelligibility in these churches. Even with the help of sound systems, values these low indicate that the speaker must pay extra attention to how he or she talks to be sure that the audience can understand him or her.

The modern churches all have values very close to 0.5, with Roihuvuori the lowest at 0.46 (still a step up from the old stone churches it had very similar results to in previous subsections) and Viikki the highest at 0.54. Once again, there is no clear divide between churches of different ages, materials or sizes. Big, wooden Laajasalo is found in the very middle with exactly the same STI as St. Matthew’s church hall made of brick and tile, right next to the concrete Kannelmäki church that had one of the highest bass ratios but has an STI of 0.52. Surprisingly, Temppeliaukio church is found in the higher end with 0.53, yet another nod to its popularity as a concert venue.

Because most of the churches have been designed as reverberant rooms, it seems the speech intelligibility has suffered. This is remedied up to a point by the sound systems installed in almost every church in use today, but as the vicars and cantors stated in chapter 5.3, most AV systems in churches are suboptimally used, often impractical, and not necessarily installed in the best possible way acoustically. While good sound systems can improve the speech intelligibility markedly, bad systems can, in worst case, make it even harder to hear what the preacher says [2]. In churches with STI as low as the values seen in e.g. Paavali and Kallio churches, the sound system would need to be expertly designed and installed, to make sure the speech intelligibility would improve and not deteriorate. The same is of course true for other churches as well, but if the non-reinforced STI is higher than 0.5 a sound system is probably more likely to improve the speech intelligibility than worsen it, even if it is not used to its full capacity. As such, if the modern churches have or would get sound systems designed for and installed in an optimal way for each individual church hall, the speech intelligibility would likely not be a problem, even if the non-reinforced
STI is not within the interval classified as good.

![STI vs distance for all measured churches](image)

**Figure 39:** Speech transmission indexes relative to the distance between the source and receiver for all measured points.

As can be seen in figure 39, the speech transmission index correlates quite well to the distance between the source and the receiver. It seems the further away the receiver is from the source, the lower the STI will be, as the reverberations in the room will affect the speech intelligiblility more.

### 7.5 Summary

Table 3 provides a quick overview of all the parameters for the churches. It would be tempting to draw the conclusion that a long reverberation time equates a low value of clarity, a high bass ratio and a low speech transmission index, but there are too many differing results even in this limited sample of churches. For example, Karjalohja has an RT over 3 seconds and a very negative value of clarity, but its bass ratio is among the lower ones. On the other hand, Munkkiniemi has one of the shorter reverberation times and a clarity close to zero, but its BR is among the highest of these churches, while its STI is close to the overall mean. If we ignore the BR, the three parameters $T_{30}, C_{80}$ and STI seem to correlate a bit better, but even there there are differing results.

Looking at these results, it seems like a typical Finnish Lutheran church has a reverberation time a little bit over two seconds, where the sound is quite clear and warm, but the speech intelligibility could be better. This gives a rough picture of what a churchgoer can expect in the Helsinki area, and a foundation for future research.
As stated in chapters 7.1 - 7.4, though, it is very hard to draw solid conclusions from the material presented here. The following conclusions are only broad strokes and may well be disproved by a more comprehensive study of the acoustics of Finnish Lutheran churches.

Table 3: Summary of the measured room acoustic criteria.

<table>
<thead>
<tr>
<th>Name of the church</th>
<th>Year built</th>
<th>$T_{30,mid}$</th>
<th>$C_{80,mid}$</th>
<th>BR</th>
<th>STI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pohja church</td>
<td>1470’s</td>
<td>2.47 s</td>
<td>-4.50 dB</td>
<td>0.85</td>
<td>0.44</td>
</tr>
<tr>
<td>Tuusula church</td>
<td>1734</td>
<td>1.23 s</td>
<td>0.75 dB</td>
<td>0.73</td>
<td>0.59</td>
</tr>
<tr>
<td>Lapinjärvi church</td>
<td>1744</td>
<td>1.29 s</td>
<td>-0.06 dB</td>
<td>0.92</td>
<td>0.56</td>
</tr>
<tr>
<td>Karjalahja church</td>
<td>1860</td>
<td>3.18 s</td>
<td>-4.27 dB</td>
<td>0.76</td>
<td>0.43</td>
</tr>
<tr>
<td>St. John’s church</td>
<td>1891</td>
<td>2.75 s</td>
<td>-4.76 dB</td>
<td>0.76</td>
<td>0.42</td>
</tr>
<tr>
<td>Kallio church</td>
<td>1912</td>
<td>3.80 s</td>
<td>-4.73 dB</td>
<td>1.10</td>
<td>0.42</td>
</tr>
<tr>
<td>St. Paul’s church</td>
<td>1931</td>
<td>3.69 s</td>
<td>-5.62 dB</td>
<td>1.47</td>
<td>0.38</td>
</tr>
<tr>
<td>Kulosaari church</td>
<td>1935</td>
<td>1.67 s</td>
<td>-0.42 dB</td>
<td>0.62</td>
<td>0.58</td>
</tr>
<tr>
<td>Munkkiniemi church</td>
<td>1954</td>
<td>1.93 s</td>
<td>-0.39 dB</td>
<td>1.09</td>
<td>0.53</td>
</tr>
<tr>
<td>Kannelmäki church</td>
<td>1968</td>
<td>2.40 s</td>
<td>-0.62 dB</td>
<td>1.18</td>
<td>0.52</td>
</tr>
<tr>
<td>Temppeliaukio church</td>
<td>1969</td>
<td>2.08 s</td>
<td>0.23 dB</td>
<td>0.99</td>
<td>0.53</td>
</tr>
<tr>
<td>Roikku church</td>
<td>1970</td>
<td>2.99 s</td>
<td>-3.75 dB</td>
<td>0.92</td>
<td>0.46</td>
</tr>
<tr>
<td>Oulunkylä church</td>
<td>1972</td>
<td>2.19 s</td>
<td>-1.81 dB</td>
<td>0.90</td>
<td>0.50</td>
</tr>
<tr>
<td>Myyrmäki church</td>
<td>1984</td>
<td>2.48 s</td>
<td>-2.07 dB</td>
<td>0.85</td>
<td>0.49</td>
</tr>
<tr>
<td>St. Matthew’s church</td>
<td>1985</td>
<td>2.36 s</td>
<td>-1.21 dB</td>
<td>0.78</td>
<td>0.51</td>
</tr>
<tr>
<td>Myllypuro church</td>
<td>1992</td>
<td>2.26 s</td>
<td>-1.31 dB</td>
<td>0.82</td>
<td>0.52</td>
</tr>
<tr>
<td>Masala church</td>
<td>2000</td>
<td>2.01 s</td>
<td>-1.10 dB</td>
<td>0.77</td>
<td>0.52</td>
</tr>
<tr>
<td>Church of the Good Shepherd</td>
<td>2002</td>
<td>2.08 s</td>
<td>-0.85 dB</td>
<td>0.78</td>
<td>0.50</td>
</tr>
<tr>
<td>Laajasalo church</td>
<td>2003</td>
<td>2.31 s</td>
<td>-1.87 dB</td>
<td>1.17</td>
<td>0.51</td>
</tr>
<tr>
<td>Viikki church</td>
<td>2005</td>
<td>1.83 s</td>
<td>0.09 dB</td>
<td>0.89</td>
<td>0.54</td>
</tr>
</tbody>
</table>

**Old stone churches:** The old, large stone churches seem to suffer from bad speech intelligibility, low values of clarity and long reverberation times. The bass ratios vary both over and under 1, showing a stronger variance than the other parameters. The long reverberation times are likely due to the high ceilings and hard, reflective material in the church halls. The small stone church built in the early 20th century showed very different values than the big stone churches, with a relatively short reverberation time, a clarity value close to zero, a low bass ratio and a speech transmission index bordering on good, reaching better values than most of the modern churches. The medium-sized old stone church could be expected to have values somewhere in between, but instead its values are very similar to the ones of the large stone churches. Whether this is due to size, age, or architecture is hard to say.
Old wood churches: The old wood churches on the other hand have speech intelligibility bordering on good, with relatively short reverberation times and clarity values close to zero. The two BR values acquired are both less than 1, but not very close to each other, making a comparison hard to make. Both churches are cruciform and almost identical in size and layout, making it hard to pinpoint where the differences come from.

Modern churches: The churches built after 1950 have reverberation times varying between 1.8 and 3 seconds, but discarding the extreme cases the average RT is very close to 2.2 seconds. The clarity values vary quite a lot, between -3.75 and 0.23, but with no apparent correlation to the size or material of the church. The STI is close to 0.5 with very few variations, while the BR varies between 0.8 and 1.2. As discussed earlier, the bass ratio is the least correlated to the other parameters, but churches of very similar material, size, and age also have very varying bass ratios. The modern church with the highest ceiling, 1970’s concrete-tile Roihuvuori church, stands out with values that more closely resemble the large, old stone churches than the other modern churches, while the results of the small, wooden Viikki church strongly resemble the old wood churches. Otherwise, the differences in size, material, and age are small enough to be negligible. Not even the churches built in consultation with an acoustician seem to have differing values.

As was concluded in section 7.4, the reverberant nature of church halls has let the speech intelligibility suffer. As a church is neither a concert hall nor an auditorium, it is hard to say what values for the different parameters would be ideal. While a short RT is better for speech intelligibility, a longer RT is needed for music. A compromise would be a value around 1.5 seconds, but that may impact the feeling of awe that the reverberant church rooms often inspire (as discussed in chapter 5), and make the acoustics too dry for community singing to feel including. As it is now, churches are seemingly made with less focus on speech and more on the music and general feeling of the room, as even the three most modern churches display quite long reverberation times.

As all four vicars expressed in chapter 5, the parameter most churchgoers notice and focus on is the speech intelligibility. Based on this, no matter how important the music is, speech intelligibility should be more important and be taken into account more than it thus far has when designing churches, or at the very least when designing the sound system for a church. It is an unfortunate situation that the sound systems used in churches are not designed as to best benefit the acoustic space, and/or not used to their full potential. If churchgoers want the Lutheran churches to be both reverberant spaces and a place where the sermon can be heard and comprehended,
more importance needs to be given to the sound systems of churches. They need to be recognized as something essential for the services of worship, instead of being the regrettably necessary technology that no one really knows how to use.
8 Conclusions

Twenty churches in the Helsinki area were measured, and the data analysed to obtain their reverberation times, clarity values, bass ratios, and speech transmission indexes. The churches varied in size from small village churches to large cathedrals, in age from built in the 1470’s to built in 2005, and were built in stone, tile, and wood. The results from each church were compared to each other.

It was found that the average reverberation time was 2.35 seconds, with the majority of the churches having an RT between 1.5 and 3 seconds. The 18th century wooden churches had much shorter reverberation times than any other measured church, while the large, old stone churches had the longest reverberation times. The reverberation times of modern churches varied between 1.8 and 2.5 seconds, with no apparent correlation to age or material.

The large majority of the churches had negative values of clarity, indicating that churches in general sound muddier. The churches with the highest ceilings had much larger negative values than the other churches, correlating with their long reverberation times, while most modern churches had values between -2 and -0.4 dB. For Lutheran churches, where music and community singing is an important part of mass, a certain degree of muddiness is desirable.

The bass ratio was the most unpredictable property, compared to the other results. The 18th century wooden churches had very dissimilar results, when they for the other parameters had very similar. The large stone churches with long reverberation times and low values of clarity were found all over the result spectrum. No architectural parameters could be found to correlate with the bass ratio.

The speech transmission indexes placed all churches except one in the tolerable bracket, and the average of all measured churches was 0.5. The 18th century wooden churches were found to have the highest STI, while the old stone churches barely made it over 0.4, and in one case only to 0.38. Average values this low indicate that sound systems are needed in churches in order to increase the speech intelligibility.

Based on these results, it is hard to make any predictions of a church’s acoustical properties based on its age, size, or material. No differences were found between churches designed in consultation with an acoustician and churches without one.

For centuries, churches have been designed as reverberant rooms, and based on the interviews with vicars and cantors, it seems that reverberation is the property that is most strongly associated with a sacred room. A reverberant space helps to associate with a heavenly dimension, and as such should be regarded as an important factor to keep in mind when designing the acoustics of churches. As long as community singing is an important a part of mass, as it is today, a longer reverberation time
(around two seconds) is also preferred to a too short one. However, this will require good sound systems to make up for the decrease in speech intelligibility that a longer RT will bring.
References


A Measurement report: Pohja church

Built in: 1470’s
Materials: stone
Date measured: 14.1.2016

Table A1: Results from the measurements done in Pohja church

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reverberation time, mid-frequencies</td>
<td>$T_{30,mid}$</td>
<td>2.47 s</td>
</tr>
<tr>
<td>Clarity, mid-frequencies</td>
<td>$C_{80,mid}$</td>
<td>-4.50 dB</td>
</tr>
<tr>
<td>Speech transmission index</td>
<td>STI</td>
<td>0.44</td>
</tr>
<tr>
<td>Bass ratio</td>
<td>BR</td>
<td>0.85</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>RH</td>
<td>28.1%</td>
</tr>
<tr>
<td>Temperature</td>
<td>T</td>
<td>18.1°C</td>
</tr>
</tbody>
</table>

Figure A1: Reverberation time in Pohja church over eight octave bands.
Figure A2: Placement of sources and receivers in Pohja church. A dash-dot line indicates the upper floor.

Figure A3: The speech transmission index for each source-receiver pair, relative to the distance between the source and the receiver in Pohja church.
B Measurement report: Tuusula church

Built in: 1734  
Materials: wood  
Date measured: 20.1.2016

Table B1: Results from the measurements done in Tuusula church

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reverberation time, mid-frequencies</td>
<td>$T_{30,mid}$</td>
<td>1.23 s</td>
</tr>
<tr>
<td>Clarity, mid-frequencies</td>
<td>$C_{80,mid}$</td>
<td>0.75 dB</td>
</tr>
<tr>
<td>Speech transmission index</td>
<td>STI</td>
<td>0.59</td>
</tr>
<tr>
<td>Bass ratio</td>
<td>BR</td>
<td>0.73</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>RH</td>
<td>13.8%</td>
</tr>
<tr>
<td>Temperature</td>
<td>T</td>
<td>15.2°C</td>
</tr>
</tbody>
</table>

Figure B1: Reverberation time in Tuusula church over eight octave bands.
Figure B2: Placement of sources and receivers in Tuusula church. A dash-dot line indicates the upper floor.

Figure B3: The speech transmission index for each source-receiver pair, relative to the distance between the source and the receiver in Tuusula church.
C  Measurement report: Lapinjärvi church

Built in: 1744
Materials: wood
Date measured: 15.1.2016

Table C1: Results from the measurements done in Lapinjärvi church

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reverberation time, mid-frequencies</td>
<td>$T_{30,\text{mid}}$</td>
<td>1.29 s</td>
</tr>
<tr>
<td>Clarity, mid-frequencies</td>
<td>$C_{80,\text{mid}}$</td>
<td>-0.06 dB</td>
</tr>
<tr>
<td>Speech transmission index</td>
<td>STI</td>
<td>0.56</td>
</tr>
<tr>
<td>Bass ratio</td>
<td>BR</td>
<td>0.92</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>RH</td>
<td>20.1%</td>
</tr>
<tr>
<td>Temperature</td>
<td>T</td>
<td>15.8°C</td>
</tr>
</tbody>
</table>

Figure C1: Reverberation time in Lapinjärvi church over eight octave bands.
Figure C2: Placement of sources and receivers in Lapinjärvi church. A dash-dot line indicates the upper floor.

Figure C3: The speech transmission index for each source-receiver pair, relative to the distance between the source and the receiver in Lapinjärvi church.
D Measurement report: Karjalohja church

Built in: 1860, renovated and got new roof in 1991 after it burned in 1970
Materials: stone, wooden roof
Date measured: 9.2.2016

Table D1: Results from the measurements done in Karjalohja church

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reverberation time, mid-frequencies</td>
<td>$T_{30,mid}$</td>
<td>3.18 s</td>
</tr>
<tr>
<td>Clarity, mid-frequencies</td>
<td>$C_{80,mid}$</td>
<td>-4.27 dB</td>
</tr>
<tr>
<td>Speech transmission index</td>
<td>STI</td>
<td>0.43</td>
</tr>
<tr>
<td>Bass ratio</td>
<td>BR</td>
<td>0.76</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>RH</td>
<td>37.9%</td>
</tr>
<tr>
<td>Temperature</td>
<td>T</td>
<td>18.4°C</td>
</tr>
</tbody>
</table>

Figure D1: Reverberation time in Karjalohja church over eight octave bands.
Figure D2: Placement of sources and receivers in Karjalohja church.

Figure D3: The speech transmission index for each source-receiver pair, relative to the distance between the source and the receiver in Karjalohja church.
E Measurement report: St. John’s church

Built in: 1891
Materials: tile, stone
Date measured: 4.2.2016

Table E1: Results from the measurements done in St. John’s church

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reverberation time, mid-frequencies</td>
<td>$T_{30,\text{mid}}$</td>
<td>2.75 s</td>
</tr>
<tr>
<td>Clarity, mid-frequencies</td>
<td>$C_{80,\text{mid}}$</td>
<td>-4.76 dB</td>
</tr>
<tr>
<td>Speech transmission index</td>
<td>STI</td>
<td>0.42</td>
</tr>
<tr>
<td>Bass ratio</td>
<td>BR</td>
<td>0.76</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>RH</td>
<td>37.4%</td>
</tr>
<tr>
<td>Temperature</td>
<td>T</td>
<td>17.4°C</td>
</tr>
</tbody>
</table>

Figure E1: Reverberation time in St. John’s church over eight octave bands.
Figure E2: Placement of sources and receivers in St. John’s church. A dash-dot line indicates the upper floor.

Figure E3: The speech transmission index for each source-receiver pair, relative to the distance between the source and the receiver in St. John’s church.
Measurement report: Kallio church

Built in: 1912
Materials: grey granite
Date measured: 5.2.2016

Table F1: Results from the measurements done in Kallio church

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reverberation time, mid-frequencies</td>
<td>$T_{30,mid}$</td>
<td>3.80 s</td>
</tr>
<tr>
<td>Clarity, mid-frequencies</td>
<td>$C_{80,mid}$</td>
<td>-4.73 dB</td>
</tr>
<tr>
<td>Speech transmission index</td>
<td>STI</td>
<td>0.42</td>
</tr>
<tr>
<td>Bass ratio</td>
<td>BR</td>
<td>1.10</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>RH</td>
<td>37.4%</td>
</tr>
<tr>
<td>Temperature</td>
<td>T</td>
<td>17.8°C</td>
</tr>
</tbody>
</table>

Figure F1: Reverberation time in Kallio church over eight octave bands.
Figure F2: Placement of sources and receivers in Kallio church. A dash-dot line indicates the upper floor.

Figure F3: The speech transmission index for each source-receiver pair, relative to the distance between the source and receiver in Kallio church.
G  Measurement report: St.Paul’s church

Built in: 1931
Materials: tile, stone
Date measured: 3.2.2016

Table G1: Results from the measurements done in St. Paul’s church

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reverberation time, mid-frequencies</td>
<td>$T_{30,mid}$</td>
<td>3.69 s</td>
</tr>
<tr>
<td>Clarity, mid-frequencies</td>
<td>$C_{80,mid}$</td>
<td>-5.62 dB</td>
</tr>
<tr>
<td>Speech transmission index</td>
<td>STI</td>
<td>0.38</td>
</tr>
<tr>
<td>Bass ratio</td>
<td>BR</td>
<td>1.47</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>RH</td>
<td>35.3%</td>
</tr>
<tr>
<td>Temperature</td>
<td>T</td>
<td>18.3°C</td>
</tr>
</tbody>
</table>

Figure G1: Reverberation time in St. Paul’s church over eight octave bands.
Figure G2: Placement of sources and receivers in St. Paul’s church. A dash-dot line indicates the upper floor.

Figure G3: The speech transmission index for each source-receiver pair, relative to the distance between the source and the receiver in St. Paul’s church.
**H Measurement report: Kulosaari church**

Built in: 1935  
Materials: concrete  
Date measured: 20.1.2016

Table H1: Results from the measurements done in Kulosaari church

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reverberation time, mid-frequencies</td>
<td>$T_{30,\text{mid}}$</td>
<td>1.67 s</td>
</tr>
<tr>
<td>Clarity, mid-frequencies</td>
<td>$C_{80,\text{mid}}$</td>
<td>-0.42 dB</td>
</tr>
<tr>
<td>Speech transmission index</td>
<td>STI</td>
<td>0.58</td>
</tr>
<tr>
<td>Bass ratio</td>
<td>BR</td>
<td>0.62</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>RH</td>
<td>13.8%</td>
</tr>
<tr>
<td>Temperature</td>
<td>$T$</td>
<td>23.1°C</td>
</tr>
</tbody>
</table>

Figure H1: Reverberation time in Kulosaari church over eight octave bands.
Figure H2: Placement of sources and receivers in Kulosaari church. A dash-dot line indicates the upper floor.

Figure H3: The speech transmission index for each source-receiver pair, relative to the distance between the source and receiver in Kulosaari church.


I Measurement report: Munkkiniemi church

Built in: 1954
Materials: concrete, tile
Date measured: 11.2.2016

Table II: Results from the measurements done in Munkkiniemi church

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reverberation time, mid-frequencies</td>
<td>$T_{30,mid}$</td>
<td>1.93 s</td>
</tr>
<tr>
<td>Clarity, mid-frequencies</td>
<td>$C_{80,mid}$</td>
<td>-0.39 dB</td>
</tr>
<tr>
<td>Speech transmission index</td>
<td>STI</td>
<td>0.53</td>
</tr>
<tr>
<td>Bass ratio</td>
<td>BR</td>
<td>1.09</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>RH</td>
<td>34.7%</td>
</tr>
<tr>
<td>Temperature</td>
<td>T</td>
<td>19.3°C</td>
</tr>
</tbody>
</table>

Figure I1: Reverberation time in Munkkiniemi church over eight octave bands.
Figure I2: Placement of sources and receivers in Munkkiniemi church.

Figure I3: The speech transmission index for each source-receiver pair, relative to the distance between the source and the receiver in Munkkiniemi church.
J Measurement report: Kannelmäki church

Built in: 1968
Materials: concrete
Date measured: 11.2.2016

Table J1: Results from the measurements done in Kannelmäki church

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reverberation time, mid-frequencies</td>
<td>$T_{30,\text{mid}}$</td>
<td>2.40 s</td>
</tr>
<tr>
<td>Clarity, mid-frequencies</td>
<td>$C_{80,\text{mid}}$</td>
<td>-0.62 dB</td>
</tr>
<tr>
<td>Speech transmission index</td>
<td>STI</td>
<td>0.52</td>
</tr>
<tr>
<td>Bass ratio</td>
<td>BR</td>
<td>1.18</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>RH</td>
<td>37.9%</td>
</tr>
<tr>
<td>Temperature</td>
<td>T</td>
<td>18.4°C</td>
</tr>
</tbody>
</table>

Figure J1: Reverberation time in Kannelmäki church over eight octave bands.
Figure J2: Placement of sources and receivers in Kannelmäki church. A dash-line indicates a shorter wall that doesn’t reach the ceiling.

Figure J3: The speech transmission index for each source-receiver pair, relative to the distance between the source and the receiver in Kannelmäki church.
K  Measurement report: Temppeliaukio church

Built in: 1969
Materials: rock, copper, concrete
Date measured: 25.1.2016

Table K1: Results from the measurements done in Temppeliaukio church

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reverberation time, mid-frequencies</td>
<td>$T_{30,mid}$</td>
<td>2.08 s</td>
</tr>
<tr>
<td>Clarity, mid-frequencies</td>
<td>$C_{80,mid}$</td>
<td>0.23 dB</td>
</tr>
<tr>
<td>Speech transmission index</td>
<td>STI</td>
<td>0.53</td>
</tr>
<tr>
<td>Bass ratio</td>
<td>BR</td>
<td>0.99</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>RH</td>
<td>28.4%</td>
</tr>
<tr>
<td>Temperature</td>
<td>T</td>
<td>20.4°C</td>
</tr>
</tbody>
</table>

Figure K1: Reverberation time in Temppeliaukio church over eight octave bands.
Figure K2: Placement of sources and receivers in Temppeliaukio church. A dash-dot line indicates the upper floor.

Figure K3: The speech transmission index for each source-receiver pair, relative to the distance between the source and the receiver in Temppeliaukio church.
L  Measurement report: Roihuvuori church

Built in: 1970
Materials: brick, concrete roof
Date measured: 12.2.2016

Table L1: Results from the measurements done in Roihuvuori church

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reverberation time, mid-frequencies</td>
<td>$T_{30,\text{mid}}$</td>
<td>2.99 s</td>
</tr>
<tr>
<td>Clarity, mid-frequencies</td>
<td>$C_{80,\text{mid}}$</td>
<td>-3.75 dB</td>
</tr>
<tr>
<td>Speech transmission index</td>
<td>STI</td>
<td>0.46</td>
</tr>
<tr>
<td>Bass ratio</td>
<td>BR</td>
<td>0.92</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>RH</td>
<td>33.3%</td>
</tr>
<tr>
<td>Temperature</td>
<td>T</td>
<td>19.2°C</td>
</tr>
</tbody>
</table>

Figure L1: Reverberation time in Roihuvuori church over eight octave bands.
Figure L2: Placement of sources and receivers in Roihuvuori church.

Figure L3: The speech transmission index for each source-receiver pair, relative to the distance between the source and the receiver in Roihuvuori church.
M Measurement report: Oulunkylä church

Built in: 1972
Materials: tile
Date measured: 8.2.2016

Table M1: Results from the measurements done in Oulunkylä church

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reverberation time, mid-frequencies</td>
<td>$T_{30,\text{mid}}$</td>
<td>2.19 s</td>
</tr>
<tr>
<td>Clarity, mid-frequencies</td>
<td>$C_{80,\text{mid}}$</td>
<td>-1.81 dB</td>
</tr>
<tr>
<td>Speech transmission index</td>
<td>STI</td>
<td>0.50</td>
</tr>
<tr>
<td>Bass ratio</td>
<td>BR</td>
<td>0.90</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>RH</td>
<td>33.2%</td>
</tr>
<tr>
<td>Temperature</td>
<td>T</td>
<td>17.9°C</td>
</tr>
</tbody>
</table>

Figure M1: Reverberation time in Oulunkylä church over eight octave bands.
Figure M2: Placement of sources and receivers in Oulunkylä church.

Figure M3: The speech transmission index for each source-receiver pair, relative to the distance between the source and the receiver in Oulunkylä church.
Measurement report: Myyrmäki church

Built in: 1984
Materials: tile, wooden panels
Date measured: 17.2.2016

Table N1: Results from the measurements done in Myyrmäki church

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reverberation time, mid-frequencies</td>
<td>$T_{30,\text{mid}}$</td>
<td>2.48 s</td>
</tr>
<tr>
<td>Clarity, mid-frequencies</td>
<td>$C_{80,\text{mid}}$</td>
<td>-2.07 dB</td>
</tr>
<tr>
<td>Speech transmission index</td>
<td>STI</td>
<td>0.49</td>
</tr>
<tr>
<td>Bass ratio</td>
<td>BR</td>
<td>0.85</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>RH</td>
<td>21.5%</td>
</tr>
<tr>
<td>Temperature</td>
<td>T</td>
<td>20.6°C</td>
</tr>
</tbody>
</table>

Figure N1: Reverberation time in Myyrmäki church over eight octave bands.
Figure N2: Placement of sources and receivers in Myyrmäki church. A dash-line indicates areas where the ceiling is lower.

Figure N3: The speech transmission index for each source-receiver pair, relative to the distance between the source and the receiver in Myyrmäki church.
O Measurement report: St. Matthew’s church

Built in: 1985
Materials: tile, brick
Date measured: 8.2.2016

Table O1: Results from the measurements done in St. Matthew’s church

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reverberation time, mid-frequencies</td>
<td>$T_{30,\text{mid}}$</td>
<td>2.36 s</td>
</tr>
<tr>
<td>Clarity, mid-frequencies</td>
<td>$C_{80,\text{mid}}$</td>
<td>-1.21 dB</td>
</tr>
<tr>
<td>Speech transmission index</td>
<td>STI</td>
<td>0.51</td>
</tr>
<tr>
<td>Bass ratio</td>
<td>BR</td>
<td>0.78</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>RH</td>
<td>31.5%</td>
</tr>
<tr>
<td>Temperature</td>
<td>T</td>
<td>20.3°C</td>
</tr>
</tbody>
</table>

Figure O1: Reverberation time in St. Matthew’s church over eight octave bands.
Figure O2: Placement of sources and receivers in St. Matthew’s church.

Figure O3: The speech transmission index for each source-receiver pair, relative to the distance between the source and the receiver in St. Matthew’s church.
Measurement report: Myllypuro church

Built in: 1992
Materials: brick, concrete, wooden panels
Date measured: 9.2.2016

Table P1: Results from the measurements done in Myllypuro church

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reverberation time, mid-frequencies</td>
<td>$T_{30,\text{mid}}$</td>
<td>2.26 s</td>
</tr>
<tr>
<td>Clarity, mid-frequencies</td>
<td>$C_{80,\text{mid}}$</td>
<td>-1.31 dB</td>
</tr>
<tr>
<td>Speech transmission index</td>
<td>STI</td>
<td>0.52</td>
</tr>
<tr>
<td>Bass ratio</td>
<td>BR</td>
<td>0.82</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>RH</td>
<td>29.1%</td>
</tr>
<tr>
<td>Temperature</td>
<td>T</td>
<td>22.6°C</td>
</tr>
</tbody>
</table>

Figure P1: Reverberation time in Myllypuro church over eight octave bands.
Figure P2: Placement of sources and receivers in Myllypuro church.

Figure P3: The speech transmission index for each source-receiver pair, relative to the distance between the source and the receiver in Myllypuro church.
Table Q1: Results from the measurements done in Masala church

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reverberation time, mid-frequencies</td>
<td>$T_{30,mid}$</td>
<td>2.01 s</td>
</tr>
<tr>
<td>Clarity, mid-frequencies</td>
<td>$C_{80,mid}$</td>
<td>-1.10 dB</td>
</tr>
<tr>
<td>Speech transmission index</td>
<td>STI</td>
<td>0.52</td>
</tr>
<tr>
<td>Bass ratio</td>
<td>BR</td>
<td>0.77</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>RH</td>
<td>26.6%</td>
</tr>
<tr>
<td>Temperature</td>
<td>T</td>
<td>20.1°C</td>
</tr>
</tbody>
</table>

Figure Q1: Reverberation time in Masala church over eight octave bands.
Figure Q2: Placement of sources and receivers in Masala church.

Figure Q3: The speech transmission index for each source-receiver pair, relative to the distance between the source and the receiver in Masala church.
R Measurement report: Church of the Good Shepherd

Built in: 1950, the new church hall was built in 2002
Materials: brick
Date measured: 10.2.2016

Table R1: Results from the measurements done in the Church of the Good Shepherd

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reverberation time, mid-frequencies</td>
<td>$T_{30,\text{mid}}$</td>
<td>2.08 s</td>
</tr>
<tr>
<td>Clarity, mid-frequencies</td>
<td>$C_{80,\text{mid}}$</td>
<td>-0.85 dB</td>
</tr>
<tr>
<td>Speech transmission index</td>
<td>STI</td>
<td>0.50</td>
</tr>
<tr>
<td>Bass ratio</td>
<td>BR</td>
<td>0.78</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>RH</td>
<td>32.6%</td>
</tr>
<tr>
<td>Temperature</td>
<td>T</td>
<td>19.9°C</td>
</tr>
</tbody>
</table>

Figure R1: Reverberation time in the Church of the Good Shepherd over eight octave bands.
Figure R2: Placement of sources and receivers in the Church of the Good Shepherd. A dash-dot line indicates the upper floor.

Figure R3: The speech transmission index for each source-receiver pair, relative to the distance between the source and the receiver in the Church of the Good Shepherd.
S Measurement report: Laajasalo church

Built in: 2003
Materials: wood
Date measured: 30.12.2015

Table S1: Results from the measurements done in Laajasalo church

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reverberation time, mid-frequencies</td>
<td>$T_{30,mid}$</td>
<td>2.31 s</td>
</tr>
<tr>
<td>Clarity, mid-frequencies</td>
<td>$C_{80,mid}$</td>
<td>-1.87 dB</td>
</tr>
<tr>
<td>Speech transmission index</td>
<td>STI</td>
<td>0.51</td>
</tr>
<tr>
<td>Bass ratio</td>
<td>BR</td>
<td>1.17</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>RH</td>
<td>26.8%</td>
</tr>
<tr>
<td>Temperature</td>
<td>T</td>
<td>20.2°C</td>
</tr>
</tbody>
</table>

Figure S1: Reverberation time in Laajasalo church over eight octave bands.
Figure S2: Placement of sources and receivers in Laajasalo church.

Figure S3: The speech transmission index for each source-receiver pair, relative to the distance between the source and the receiver in Laajasalo church.
Measurement report: Viikki church

Built in: 2005
Materials: wood
Date measured: 12.2.2016

Table T1: Results from the measurements done in St. Paul’s church

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reverberation time, mid-frequencies</td>
<td>$T_{30,\text{mid}}$</td>
<td>1.83 s</td>
</tr>
<tr>
<td>Clarity, mid-frequencies</td>
<td>$C_{80,\text{mid}}$</td>
<td>0.09 dB</td>
</tr>
<tr>
<td>Speech transmission index</td>
<td>STI</td>
<td>0.54</td>
</tr>
<tr>
<td>Bass ratio</td>
<td>BR</td>
<td>0.89</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>RH</td>
<td>31.2%</td>
</tr>
<tr>
<td>Temperature</td>
<td>T</td>
<td>20.8°C</td>
</tr>
</tbody>
</table>

Figure T1: Reverberation time in Viikki church over eight octave bands.
Figure T2: Placement of sources and receivers in Viikki church. A dashed line indicates areas where the ceiling is lower.

Figure T3: The speech transmission index for each source-receiver pair, relative to the distance between the source and the receiver in Viikki church.