Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Information Technology and Electrical Engineering
Department of Electronic Systems

Erlend Bolstad

Room acoustic conditions in primary schools

Master's thesis in Electronic systems design - Acoustics
Supervisor: Peter Svensson, NTNU & Bård Støfringsdal, COWI
June 2019

NTNU
Norwegian University of
Science and Technology

Erlend Bolstad

Room acoustic conditions in primary schools

Master's thesis in Electronic systems design - Acoustics
Supervisor: Peter Svensson, NTNU & Bård Støfringsdal, COWI
June 2019

Norwegian University of Science and Technology
Faculty of Information Technology and Electrical Engineering
Department of Electronic Systems

NTNU
Norwegian University of
Science and Technology

Abstract

Sound pressure levels in 8 primary schools in Trondheim have been measured and sorted for the following categories: plenary activity, individual work, group work, practical work and film. Measurements, together with observation of the activities, were conducted during lectures. The sound levels were analysed in relation to room dimensions, acoustic conditions and occupancy of the rooms. Plenary activity accounted for 46% of the time spent on educational activities, and together with individual work, it occupied 79% of the time. From this, it is suggested that acoustic conditions should favour these activities in primary schools.

Noise conditions in plenary activities provide the most interesting result from the measurements, due to a large sample size compared to the other activities. The average activity noise level, defined as noise generated by the pupils during plenary activity, was found to be 40.3 dB in enclosed classrooms and 42.9 dB in open-plan spaces. Activity noise is detrimental to speech communication, and its level could be used as a noise reference in predictions of speech intelligibility with parameters like STI and U_{50}.

The amount of measurements are limited compared to similar studies, but significant correlation between sound levels and room acoustic conditions indicates relationships that can be further studied. From the measured sound levels, a statistically significant correlation ($p_s < 0.05$) was found between activity noise and room height in enclosed classrooms. The occupancy relative to the acoustic capacity, the latter a concept developed for restaurants, was also significantly correlated to activity noise in plenary activity. Interestingly, activity noise was not significantly correlated to reverberation time or background noise, even though these are given requirements in the Norwegian building regulation NS 8175:2012. However, the signal-to-noise ratio in plenary activity was significantly correlated to background noise in addition to the occupancy relative to the acoustic capacity. The average sound level in other activities than plenary did not correlate with acoustic conditions.

On average, the reverberation time was 0.54 s in enclosed classrooms, and 0.51 s in open-plan spaces. Out of 14 enclosed classrooms, 8 complied with the maximum limit of 0.5 s in NS 8175. However, 0.4 s is considered superior conditions. Use of short reverberation times have been criticised for negative effects on vocal comfort, and it is interesting that no significant correlations were found between noise levels and the range of reverberation times in this study. Conditions in Norwegian classrooms could be used for further studies on finding an optimal reverberation time, and for investigating whether room height could be included as a parameter in the building regulation.

Samandrag

Lydtrykknivå har blitt målt ved 8 barneskular i Trondheim, og sortert for dei følgjande kategoriane: plenumsaktivitet, individuelt- gruppe- og praktisk arbeid, samt film. Lydmålingar og observasjon av aktivitet vart utført i undervisning, og lydnivåa vart analysert med hensyn på romdimensjonar, akustiske forhold og antal elevar i klasserommet. Plenumsaktivitetar stod for 46% av den totale tida brukt på undervisningsaktivitet, og saman med individuelt arbeid utgjorde desse aktivitetane 79% av undervisningstida. Utfrå denne fordelinga kan det argumenterast for at romakustiske forhold som er gunstige for nemnde aktivitetar bør tilleggjast størst vekt i prosjektering av nye klasserom.

Plenumsaktivitet har størst datagrunnlag i målingane, og støyforholda i denne aktiviteten utgjer det mest interessante resultatet i studiet. Det gjennomsnittlege aktivitetsstøynivået, definert som støy generert av elevar, var 40.3 dB i lukka klasserom og 42.9 dB i baseskular. Aktivitetsstøy er forstyrrande for talekommunikasjon, og nivåa som er funne kan nyttast som støyreferense i berekningar av taletydelegheit med parameter som STI og U_{50}.

Datagrunnlaget er avgrensa samanlikna med liknande studiar, men signifikante korrelasjonar mellom lydnivå og romakustiske forhold kan likevel indikera samanhengar som kan undersøkast nærare i vidare studiar. Basert på målingane i dette studiet er aktivitetsstøy statistisk signifikant korrelert ($p_s < 0.05$) med romhøgde i lukka klasserom. Antalet elevar relativt til akustisk kapasitet, det siste ein modell utvikla for restaurantar og kaféar, er også signifikant korrelert med aktivitetsstøy. Etterklangstid og bakgrunnsstøy er gitt grenseverdiar i byggestandarden NS 8175:2012. Likevel, og ulikt det som er funne i tidlegare studiar, er aktivitetsstøy ikkje signifikant korrelert med etterklangstid eller bakgrunnsstøy basert på data frå dette studiet, men signal-til-støy forholdet i plenumsaktivitet var signifikant korrelert med bakgrunnsstøy. Gjennomsnittleg lydnivå i andre aktivitetar enn plenumsaktivitet var ikkje korrelert med romakustiske forhold.

I gjennomsnitt var etterklangstida 0.54 s i lukka klasserom og 0.51 s i baseskular. Av 14 lukka klasserom var 8 i henhold til maksimumsverdien på 0.5 s i NS 8175. Samstundes reknar standarden 0.4 s for å vera optimalt i klasserom. Korte etterklangstider har blitt kritisert for negativ innverknad på talekomfort, og det er interessant at ingen signifikant korrelasjon mellom støynivå og etterklangstid vart påvist i dette studiet. Med dei relativt korte etterklangstidene funne i norske klasserom, kan vidare studiar i desse romma nyttast til å finna ei optimal etterklangstid, og i tillegg vurdera om krav til høgde kan takast med i NS 8175.

Preface

This master's thesis makes up the final stage of my master's degree in acoustics at the Department of Electronic Systems at Norwegian University of Science and Technology.

The topic of classroom acoustics was suggested by Bård Støfringsdal from COWI, and I also made a preparatory project thesis on the same topic in the fall semester of 2018. My motivation for studying acoustics is related to an interest in music, sound and technology. I also have 6 years experience as a teacher in upper secondary school, and classroom acoustics therefore combine professional experience and personal interests.

Professor Peter Svensson has been the main supervisor for this thesis. Through weekly meetings we have had discussions on e.g. measurement methods, Matlab scripts for analysing data and various room acoustic topics. I would like to thank Peter for his contribution and interest in the project, and for providing excellent explanations of topics I was unsure of.

Bård Støfringsdal has been co-supervisor. His interest in the topic and experience from work as an acoustics advisor was valuable for the development of the project. I would like to thank Bård for suggesting the topic and for our discussions on measurements and analysis.

One school was visited during pilot measurements, and eight schools were visited for measuring the data presented in the thesis. I would like to thank the headmasters, teachers and pupils who welcomed me and made it possible to carry out the measurements. Also, I would like to thank Åse Dalseth Austigard from Trondheim kommune for helping me getting an overview of the primary schools in Trondheim, and for sharing experiences with previous work on acoustics in schools.

I would like to thank Marius, Paula and Leo from COWI and Tim Cato Netland from NTNU for helping me with equipment for the measurements.

I would also like to thank my family and extended family for supporting my choices and believing in me, even though I have spent many years on studying.

Finally, I wish to thank Kirsti for her support and patience, and for helping me with reading and spell checking the thesis.

Erlend Bolstad
7th June 2019

Contents

1 Introduction

1.1 Motivation

Classroom acoustics is about designing rooms to fit various educational activities having different acoustic preferences. Most countries have building regulations defining limits for reverberation time and background noise from technical installations. Some also include speech transmission parameters. The criteria for acoustic conditions in the Norwegian standard NS 8175:2012 are divided into four sound classes (A to D). Class A represents limit values providing the most superior sound conditions, and class D the most inferior [1]. In Norway, the building regulation TEK17 refers to NS 8175:2012 [1] in terms of classroom acoustics, and minimum class C is required for new buildings. The last revision of the standard was in 2012, but a new revision is under work at the time of writing. A temporary version of the revision contains no changes in room acoustics for schools. In discussions with representatives of The Acoustics Experts Group of the Union of Consultants in Norway (Rådgivende ingeniørers forening, RIF), it is argued that rooms for educational purpose need to have a more refined approach than what today's standard is presenting. The following topics are addressed:

1. The idea that lower reverberation time always leads to better acoustics in rooms used for speech performance is challenged. Today, class A and B requires a reverberation time of 0.4 seconds, class C, 0.5 seconds and class D, 0.6 seconds.

2. It is argued that sound classification of class A and B should be directly related to the perceived speech intelligibility, and not based on reverberation time alone.

Even though building standards are established and based on previous studies on classroom acoustics, schools and their teaching methods are constantly developing, and the requirements for acoustic design might need to develop accordingly. Due to cultural differences, school and learning practices can vary across countries, and the differences need to be considered when evaluating studies from other countries. Another important perspective is the connection between age and hearing development. Today, the building regulation is the same from primary school to universities. However, for the younger pupils, both hearing and vocabulary is under development, and therefore, requirements for speech intelligibility are higher than for adults.

This study aims at documenting the present acoustic conditions in primary school classrooms.

By measuring and analysing sound pressure levels during various activities and in different rooms, correlations between room design and activity sound levels could be studied. The study builds on previous research within the field of classroom acoustics. The next section will present main findings from much published research.

1.2 Previous research

Classroom acoustics is a field where extensive research has been conducted over the last 40 years. A majority of the work is about plenary activities, that is, activities where the teacher speaks and the pupils listen or respond to the teacher's questions. Parameters describing speech intelligibility has been important, and the correlation with noise and reverberation time has been studied through various experiments. Bradley has been involved in several studies on speech intelligibility. He introduced U_{50} as a quantity for predicting speech intelligibility, and has also analysed the relationship between reverberation time and speech intelligibility parameters [2][3]. Hodgson et al. developed a model for speech- and background noise levels in university lectures based on normal distribution fittings on histograms of sound levels [4], and Shield et al. have studied activity sound levels in British schools [5]. Also, Pelegrín-García et al. have studied the room acoustic conditions in terms of the vocal comfort for the teacher, thus problematising the idea of lower reverberation time providing better conditions in classrooms [6].

Background noise is mentioned as an important parameter, but the noise situation might be more complex when the classroom is occupied with teachers and pupils. For speech intelligibility parameters, the noise component needs to be realistic in order to predict the conditions accurately. Also, noise levels from other activities than the plenary situation could be of interest when designing room acoustics for classrooms.

The building regulations in Norway are stricter than in many foreign countries. However, little research is found on how the typical Norwegian classrooms function in terms of acoustics and sound levels during activities. More studies could provide basis for future optimisation of these regulations, from where this study is motivated.

1.3 Project objective

Based on the intention of optimising building regulations, data from Norwegian classrooms could provide valuable insights in how rooms with shorter reverberation time and lower background noise functions. The project objective is: What are the sound levels in a typical Norwegian classroom during different educational activities, and how do they correlate with room design? Five categories of activity will be evaluated. The first four are identical to the categories used by Shield et al. [5], and the fifth is suggested in this study due to activities occurring that did not fit into the other categories.

- Plenary activity.

  The teacher or one pupil at the time speaks to everyone.

- Group work.

  The pupils discuss and solve tasks with their fellow pupils.

- Individual work.

  Concentrated work or reading, but some conversations can occur.

- Film

  Playback of video or audio content through loudspeakers.

- Practical activity.

  A category for activities that does not fit in the previous ones. This includes physical activities, activities which use special educational materials or tools and activities similar to games.

By measuring a selection of lectures in 5th to 7th grade in primary schools in Trondheim municipality, average sound levels for the different categories of activity can be found. Also, the measured sound levels will be analysed for correlations with room acoustic conditions. The purpose of the study is to evaluate these conditions in classrooms used in Norwegian primary schools today, and provide data and results that can be useful in future revisions of the building regulation, NS 8175:2012.

The collected data can also give an indication of how much time is spent on the different activities. A room design that is only based on plenary activities might not function very well on other activities.

1.4 Structure

Chapter 2 of the thesis will cover fundamental acoustic theory about sound pressure levels, room acoustics and perceptual effects. The chapter also includes a short section on statistics which is used in analysis of measured data. Further, chapter 3 describes how measuring of lectures and room acoustic conditions was conducted, and how statistics was used to analyse measured data. The chapter also includes information about schools visited in the study, and distribution of data in terms of subjects, grades, activities and rooms. Chapter 4 presents the results. It starts with a description of conditions in unoccupied classrooms. Further, the sound pressure levels are given for the five activity categories, and analysis of correlation with room design are carried out. In chapter 5, the results will be discussed and suggestions for further research given, and finally, chapter 6 contains a conclusion that summarises the most important findings from the study.

2 Theory

This chapter presents theory used in the measurements and analysis of the study. Since sound levels are studied, the chapter starts with a section on what sound pressure levels are, and how they can be presented in different weighted representations. Further, a section on room acoustics includes theory relevant both for how measurements are conducted, and how the measured sound levels are analysed with respect to room acoustic conditions. Finally, a short presentation of statistics is given, as statistics are used in the analysis of sound levels with respect to room acoustic conditions.

2.1 Sound pressure level

Sound is small pressure deviations from the static air pressure, propagating as a pressure wave from the generating source. Sound pressure can be measured with a pressure sensor (microphone) and the level is expressed in decibels [dB], which is the ratio between the measured root-mean-squared pressure (p) in Pascals [Pa] and a reference pressure (p_{ref}). The reference pressure corresponds to the hearing threshold at 1000 Hz of human beings. A logarithmic scale is used due to a large deviation between the lowest and highest pressure levels. The definition of sound pressure level (SPL) is given by the general equation 2.1,

$$L_p = 20 \log \frac{p}{p_{ref}} \text{ [dB]} \tag{2.1}$$

where p_{ref} is 20 μPa.

2.1.1 Time-weighting

SPL can have extensive variations over time. A sound level meter shows the level time-weighted with a fast (125 ms) or slow (1 s) setting, which essentially is a low-pass filter used on the rapid fluctuations of SPL. Time-varying SPL can be registered in sampled levels with a defined sample time.

2.1.2 Time-averaging

Another representation is the time-averaged SPL, also called the equivalent continuous sound pressure level. This parameter presents the average level over a given time interval, and is calculated from equation 2.2,

$$L_{eq,T} = 10 \log \frac{\frac{1}{T} \int_0^T p^2(t)dt}{p_{ref}^2} \text{ [dB]} \tag{2.2}$$

where T is the averaging interval.

SPL can also be presented as a statistical parameter. L_n describes the SPL that is exceeded n% of the time. L_{A90} is frequently used for rating background noise [7].

2.1.3 Frequency weighting

SPL can be divided into levels in separate frequency bands (normally 1/1 or 1/3 octave bands), and SPL is the logarithmic sum of the levels in each frequency band. However, the hearing sensitivity is not linear across frequency, and the unweighted representation of SPL is therefore not a good indicator of the experienced level. Equal loudness-curves describe the average sensitivity to levels in terms of frequency. The curves are shown in fig. 2.1, and it is observed a lower sensitivity in the lower and higher frequencies.

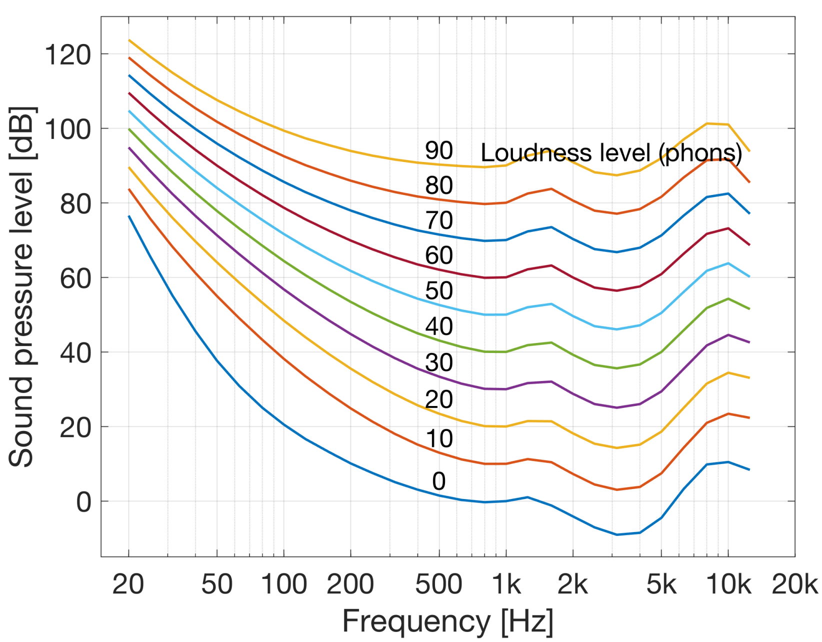

Figure 2.1: Equal-loudness curves, sensitivity to levels in terms of frequency.

As an example, a sound with low frequency-focused content will not be perceived as loud as a sound with mid frequency-content even though represented by the same SPL. A- and C-weighted filters are used for low and high sound pressure levels respectively. Fig. 2.2 shows the A-weighting curve together with the 40 phon equal-loudness curve. Noise measurements are typically performed with A-weighting. $L_{Aeq,8h}$ will give the A-weighted, time-averaged SPL over an interval of 8 hours.

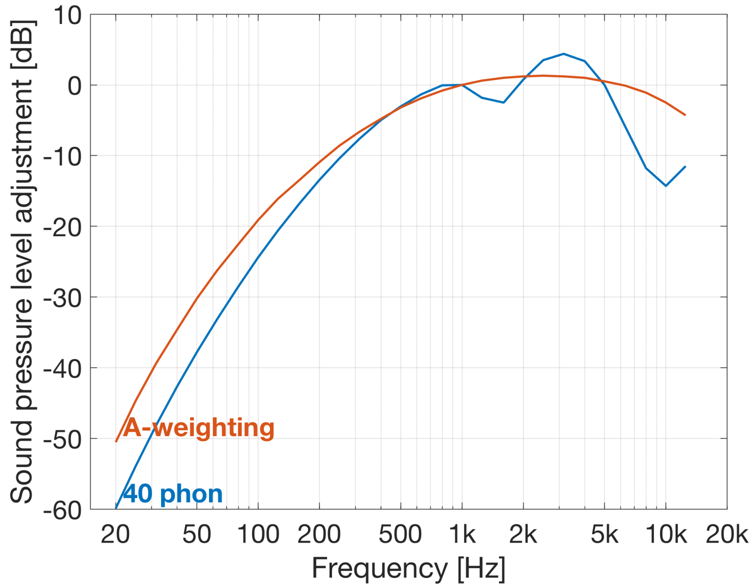

Figure 2.2: Red curve: A-weighting level adjustments. Blue curve: 40 phon equal-loudness curve

2.2 Room acoustics

The exact solution for the sound field in a room can be provided by the wave equation. However, an analytical solution is only possible for a few specific geometries. Therefore, statistical and geometric acoustics have been developed as approximations to the acoustic conditions in rooms. Statistical methods will be discussed here.

2.2.1 Statistical methods

Statistical acoustics is an approximation to the exact solution. One must therefore be aware of the limitations when using the method. A constant energy density is assumed across the room, and this ignores the fact that there will be room modes where the room dimensions interact with certain frequencies and result in resonances. Room resonances can be well perceived in the lower frequency range, making statistical methods less useful here. However, as the frequency increases, the modes get closer to each other and starts to overlap. Then, they are not perceived any more. The Schroeder frequency is found from equation 2.3 and is the frequency where we can start assuming constant energy density across the room [8]. Above this frequency, statistical methods can be a good approximation.

$$f_s = 2000\sqrt{\frac{T}{V}}\ [\mathrm{Hz}] \tag{2.3}$$

2.2.2 Reverberation

Reverberation time, T, is the classical parameter in room acoustics. It is defined as the time it takes for the space-averaged sound energy density in an enclosure to decrease to a millionth, or equivalently, that the sound pressure level is decreased by 60 dB, measured from the time the sound source is turned off. In practice, it requires a very loud test signal to achieve 60 dB dynamic difference, so it is common to measure lower dynamic differences and extrapolate the curve to 60 dB reduction. T_{20} and T_{30} are widely used in measurements, and they both measure from the time the decay curve has decreased with 5 dB from the peak level. Then, the time interval to 25 dB (T_{20}) and 35 dB (T_{30}) reduction is measured, and extrapolation is performed [9].

2.2.3 Absorption

The reverberation in a room is connected to the amount of absorption through Sabine's formula (equation 2.4), which is probably the best-known formula in room acoustics.

$$T = 0.163\frac{V}{A}\ [\mathrm{s}] \tag{2.4}$$

The equation connects room volume, V, reverberation time, T, and absorption area, A. The absorption area can be separated into different materials with an absorption factor, α, and a defined surface area, S.

$$A = \sum \alpha_i S_i\ [\mathrm{m}^2] \tag{2.5}$$

Sabine's formula is popular and much in use due to its simplicity. However, it does not function well for all kinds of rooms. Eyring's formula is typically more accurate for rooms with a high amount of absorption, and will give shorter reverberation times compared to Sabine in these rooms. Eyring's formula will not be used in this study.

2.2.4 Sound fields

In room acoustics, a distinction between two separate components of the sound field is much used. These are the direct- and reverberation fields

2.2.4.1 Direct field

The field closest to the sound source is the direct field. The sound in this field is dominated by the direct sound from the source, similar to what can be measured in free field, e.g. in an anechoic chamber. SPL for a point source is here given by the sound power level, L_W, and the distance from the source, r, through equation 2.6.

$$L_p = L_W + 10 \log \frac{1}{4\pi r^2} \text{ [dB]} \tag{2.6}$$

2.2.4.2 Reverberation field

As the distance to the source increases, the reflections from room surfaces will contribute to the sound field, and eventually, the reflections will dominate over the direct sound. This is defined as the sound field where all directions of sound propagation contribute equally to the sound intensity [8]. The SPL will here be dependent on the absorption, A, of the room surfaces, and equation 2.6 is expanded to equation 2.7.

$$L_p = L_W + 10 \log \left(\frac{1}{4\pi r^2} + \frac{4}{A} \right) \text{ [dB]} \tag{2.7}$$

The sum of direct sound and reverberation is plotted as the red, solid line in figure 2.3. The red dotted and the blue dotted line shows the reverberation and the direct sound contributions individually.

Barron proposed a revised theory based on measurements in concert halls in 1988. Results from the measurements showed that the reverberation level also decreased with distance [10]. The revised formula is presented in equation 2.8,

$$L_p = L_W + 10 \log \left(\frac{1}{4\pi r^2} + \frac{4}{A} e^{\frac{-2\delta r}{c}} \right) \text{ [dB]} \tag{2.8}$$

where

$$\delta = \frac{3 \ln 10}{T} \tag{2.9}$$

Figure 2.3 shows the effect of Barron's revised formula. The blue, solid line is the sum of direct sound and reverberation according to Barron's formula. It is observed that the total SPL slightly decreases with distance in the reverberation field, due to the reverberation component (yellow dotted line) decreasing over distance.

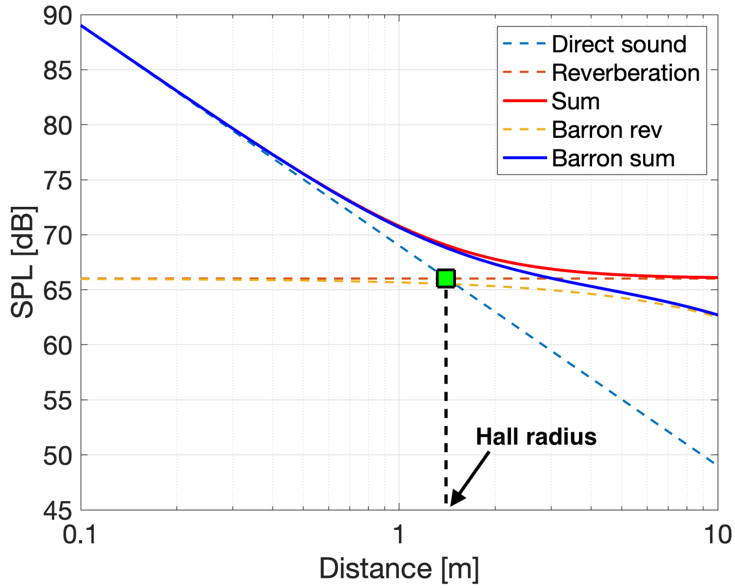

Figure 2.3: SPL over distance, Classical and Barron's revised formula. Hall radius, r_h, is indicated on the distance axis.

2.2.4.3 Source directivity

Not all sound sources are point sources. Directive sources do not radiate with the same strength in all directions, and the radiation pattern is defined with a directivity factor, DF. A point source has $DF = 1$, whereas a half-sphere source has $DF = 2$. Introducing directivity, equation 2.8 is transformed to equation 2.10.

$$L_p = L_W + 10 \log \left(\frac{DF}{4\pi r^2} + \frac{4}{A} e^{\frac{-2\delta r}{c}} \right) \text{ [dB]} \tag{2.10}$$

2.2.4.4 Hall radius

It is observed that the term for the direct field, $\frac{1}{4\pi r^2}$, decreases exponentially with the distance, r. The distance where the term for the reverberation field starts to dominate, is named the hall radius, r_h. The location of the hall radius is indicated in figure 2.3 and can be found from equation 2.11.

$$r_h = \frac{A \cdot DF}{16\pi} \text{ [m]} \tag{2.11}$$

2.2.4.5 Strength, G

G is the room strength, how the room is perceived to amplify the voice when speaking. It represents how much the room reflections enhance the source signal in a listening position. G is calculated by measuring the sound pressure level at a position in the room, and then subtracting the level of the same source at a distance of 10 meters in free-field (see equation 2.12) [11].

$$G = L_p - L_{p,free-field,10m} \text{ [dB]} \tag{2.12}$$

G can also be predicted from the absorption of the room [11]. Here, it is assumed that the mean free path in the room is $\frac{4V}{S}$. Ignoring the direct sound and including Barron's revised formula, G in distance of r from the source can be predicted from equation 2.13.

$$G = 10\log\left(\frac{1600\pi}{A}e^{\frac{-2\delta r}{c}}\right) \text{ [dB]} \tag{2.13}$$

One can also predict G as a mean value across an interval between distance r_1 and r_2. The expression is presented in equation 2.14, and the principal is shown in figure 2.4

$$G_{mean} = 10\log\left(31200\frac{T}{DF \cdot V} \cdot \frac{1}{r_2 - r_1} \cdot \frac{c}{2\delta}\left(e^{-\frac{2\delta r_1}{c}} - e^{-\frac{2\delta r_2}{c}}\right)\right) \text{ [dB]} \tag{2.14}$$

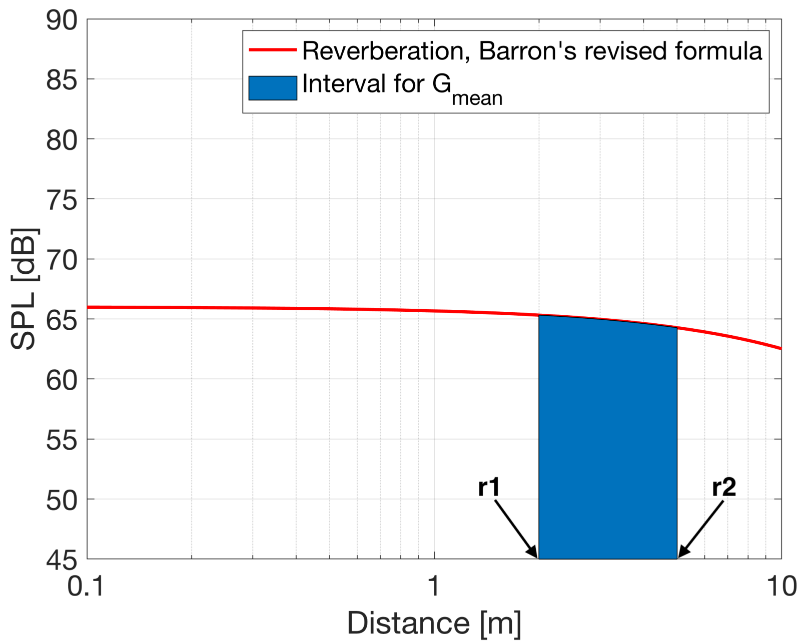

Figure 2.4: G_{mean} from interval between r_1 and r_2

2.3 Perceptual effects

Perceptual effects have been established to describe the experience of acoustics in a room. Both the speaker's and the listeners' experience are affected by these parameters.

2.3.1 Speech transmission index, STI

The speech transmission index is a parameter designed to describe how accurate speech is perceived in a room. It was developed by Houtgast and Steeneken and is measured in an empty room using a amplitude modulated signal [12]. The idea is that reverberation and/or noise will eliminate rapid fluctuations in the amplitude of the signal. By testing the room with different modulation speeds, the influence of the reverberation and noise on the speech intelligibility is approximated [8]. The result is given as values from 0 to 1.

2.3.2 Useful-to-detrimental ratio, U_{50}

U_{50} is the useful-to-detrimental ratio, and it was suggested by Bradley in 1986. Here, the useful sound means the direct sound energy, (E_d), and the early sound energy arriving during the first 50 ms after the direct sound, (E_e). The detrimental sound consists of the late sound energy arriving later than 50 ms after the direct sound, (E_l), and the background noise energy (E_n) [2][3].

$$U_{50} = 10 \log \frac{E_d + E_e}{E_l + E_n} \text{ [dB]} \tag{2.15}$$

2.4 Restaurant acoustics

Some activities in classrooms have similarities with the field of restaurant acoustics. Group work and other activities where several people speak at the same time are examples of these activities. Sound pressure levels will increase, due to the Lombard effect, and previous research can give recommendations for room design and occupancy.

2.4.1 Lombard effect

When speaking, one usually adjust the speech level to the background noise. Rindel has developed a model for predicting the ambient noise level in a room with respect to the occupancy [13].

$$L_{N,A} = 93 - 20 \log \left(g \left(\frac{0.16V}{N \cdot T} + A_p \right) \right) \text{ [dB]} \tag{2.16}$$

where g is the average number of people per speaking person (usually $g = 2 - 4$), N is the total number of people in the room and A_p is the absorption per person ($A_p = 0.2 - 0.5$ m^2).

2.4.2 Absorption per speaking person

Rindel's work includes a recommendation for absorption area per speaking person in terms of the wanted SNR (eq. 2.17),

$$\frac{A}{N_s} = 10^{\frac{(SNR+14)}{10}} \tag{2.17}$$

where N_s is the group size ($N_s = \frac{N}{g}$).

2.4.3 Acoustic capacity

Rindel has also suggested acoustical requirements for restaurants based on the acoustic capacity [13]. The acoustic capacity describes the maximum number of persons occupying a room as a function of room volume and reverberation time. With a ambient noise level of 71 dB at 1 m distance, a SNR of -3 dB is possible for a maximum number of people (N_{max}):

$$N_{max} \cong \frac{V}{20T} \tag{2.18}$$

It should be noted that -3 dB is on the borderline between a sufficient and an insufficient SNR for vocal communication, so these are not excellent conditions [13].

To describe the number of people in the room (N) relative to the acoustic capacity, an acoustic utilisation ratio ($N_{utilisation}$) can be used.

$$N_{utilisation} = \frac{N}{N_{max}} \tag{2.19}$$

2.5 Statistics

Statistics can be used to analyse large data sets and determine whether different variables are related. It can also be established whether the relation is of statistical significance. Further, regression can be used to describe the relationship between the variables. This study will use statistics to analyse the relationship between sound levels and room acoustic conditions. The following three sections presents the statistical concepts correlation, statistical significance and regression.

2.5.1 Correlation

The correlation coefficient, r_s, is a measure of how close two variables are to having a linear relationship with each other. r_s is found by dividing the covariance between the variables with the variance of each variable. r_s is then found to be a value between -1 and 1. Here, 0 means no linear relationship, and the higher the absolute value, the stronger is the relationship. A positive r_s indicates that an increase in e.g. reverberation time, T leads to an increase of the sound level, L_p, and a negative r_s indicates the opposite [14]. The empirical correlation in a data set is found from the following equation:

$$r_s = \frac{\sum_{i=1}^{n}(T_i - \overline{T})(L_{p,i} - \overline{L_p})}{\sqrt{\sum_{i=1}^{n}(T_i - \overline{T})^2} \cdot \sqrt{\sum_{i=1}^{n}(L_{p,i} - \overline{L_p})^2}} \tag{2.20}$$

Some limitations should be discussed regarding use of correlation. Figure 2.5 shows two examples of data sets. They both indicate a relationship between two variables, the left one is linear, and the right one is non-linear. Considering the non-linear graph, it can be realised that if a study collects the first quarter of the range of the horizontal variable, the result will be no correlation, even though a larger range of variables would provide a different result. It can also be realised that linear regression will show a low correlation due to the exponential increase observed in the right graph.

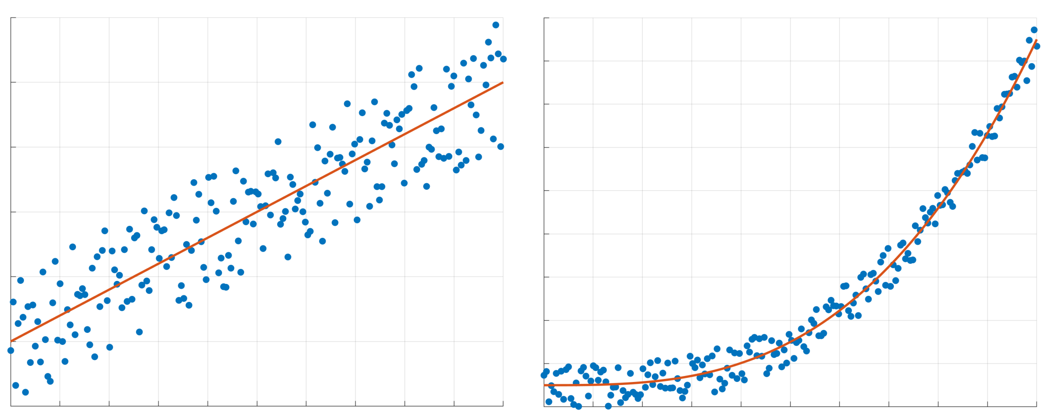

Figure 2.5: Example of linear and non-linear relationship

2.5.2 Statistical significance

By using statistical significance, one is testing how unlikely it is that the null hypothesis is true. The null hypothesis, H_0, is that there is no correlation between the variables. The probability value, p_s, is used to represent the level of statistical significance. p_s indicates the probability for H_0 to be discarded by error [14]. In this study, $p_s < 0.05$ is considered statistically significant.

2.5.3 Regression

Linear regression provides coefficients $\hat{\alpha}$ and $\hat{\beta}$ to express a straight line connecting e.g. reverberation time, T and sound level, L_p. This gives an expression on the form $\hat{L_p} = \hat{\alpha} + \hat{\beta}T$. A frequently used method is the least-squares line fit. Here, the square of the deviations between each data point and a straight line are summed. When the sum of squared distances is at the minimum, the line is called a least-squares line fit. The coefficients are given by the following equations:

$$\hat{\beta} = \frac{\sum_{i=1}^{n}(T_i - \overline{T})(L_{p,i} - \overline{L_p})}{\sum_{i=1}^{n}(T_i - \overline{T})^2} \tag{2.21}$$

$\hat{\beta}$ can also be found from the correlation, r_s, and the standard deviations of T and L_p:

$$\hat{\beta} = r_s \frac{\sigma_{Lp}}{\sigma_T} \tag{2.22}$$

$$\hat{\alpha} = \overline{L_p} - \hat{\beta}\overline{T} \tag{2.23}$$

3 Methodology

The data collection for this study took place in primary school classrooms. It was chosen to study a young group of pupils since their hearing is less developed than for older pupils. Hence, they are an important target group for standards in room acoustic design. Grades five to seven in primary school were selected for the study, assuming that they have more established patterns of classroom behaviour than pupils in the lower grades. Measurements were conducted in 8 schools in the municipality of Trondheim in Norway between February 28th and April 10th 2019. Lectures in Mathematics, Science, Norwegian, English, Social studies and Religion, philosophies of life and ethics (RLE) were followed.

The measurements and analysis in this study are designed to describe three different sound pressure levels:

- The average sound pressure level
- The activity noise level
- The background noise level (from unoccupied classrooms)

In this chapter, methods for measurement of sound levels in the classrooms are presented, in addition to methods for measuring the room acoustics. Finally, a presentation of the participating schools and facts on the distribution of measurements are given.

3.1 Measuring sound levels during lectures

In this study, sound pressure levels were measured during lectures. An observer was present in the classrooms, and time instances for when different activities started or interruptions occurred were noted in an observation sheet. The schools required a criminal record certificate from the observer to give access to classrooms during lectures. Dependency of an observer could have been avoided by recording audio from the lectures, but due to the General Data Protection Regulation, this would require permission from all the participants and their parents.

The sound pressure level was recorded with fast time-weighting, and the equivalent level, L_{eq}, was output with 200 ms sample time in 1/3 octave bands. Later, a script in Matlab was used to sort the levels for activity based on the observation sheet.

3.1.1 Correction for background noise

SPL can be affected by background noise if the measured level is close to the background noise level. ISO 16032:2004 introduces a procedure for correcting the measured level of a technical installation to the stationary background noise level [15]. This procedure can also be used to correct the measured SPL to background noise. All sampled levels in 1/3 octave bands are converted to octave bands and corrected for background noise prior to further analysis. The correction is especially important for testing correlations between activity noise and other parameters independently of the background noise.

The correction is based on the level difference, ΔL, between the measured level (including background noise), L_1, and the background noise level, L_2.

$$\Delta L = L_1 - L_2 \text{ [dB]} \tag{3.1}$$

Further, the correction, K, is found from equation 3.2

$$K = \begin{cases} 2.2 & , \Delta L \leq 4 \\ -10\log(1 - 10^{(-0.1\cdot\Delta L)}) & , 4 < \Delta L < 10 \\ 0 & , \Delta L \geq 10 \end{cases} \tag{3.2}$$

Finally, the correction is made from equation 3.3

$$L = L_1 - K \text{ [dB]} \tag{3.3}$$

3.1.2 Plenary activity

During plenary and film activities, the average sound pressure level can be considered as the signal component. It is the level generated by the person speaking or the audio track of the film. The noise component will then be the sum of activity and background noise. Activity noise describes the noise produced by the behaviour of the people occupying the room. The noise could be from steps, moving of furniture, coughing, whispering, writing on paper/computer etc. A principal sketch of the signal- and noise component in the time domain is shown in figure 3.1.

The total noise is detrimental to perception of speech in the plenary activities. Parameters like speech-transmission index (STI) and the acoustical energy ratio U_{50} needs a realistic measure of noise to predict speech perception accurately.

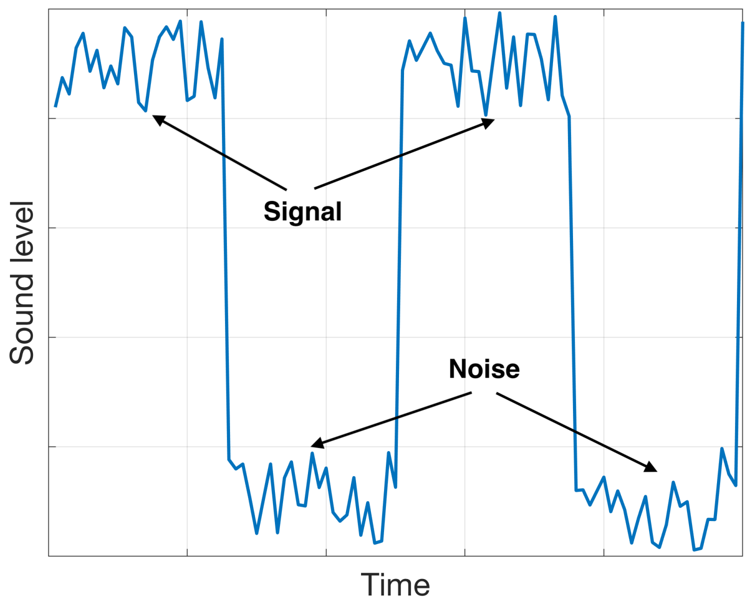

Figure 3.1: Principal sketch of signal- and noise component as a function of time in plenary activity

3.1.3 Other activities

During activities like individual-, group- and practical work, the distinction between a signal- and a noise component is of less interest. Here, the average sound pressure level describes the total noise level for the activity. Finding whether this level is affected by the acoustic design of the room is of interest.

3.1.4 Position of sound analyser

The sound analyser was placed at various positions in the classrooms. The aim was to find a place where it was not disturbing any activities, and the different room sizes and furnishing required different positions for the analyser. However, it was always placed in the reverberation field (see section 2.2.4.2) when considering the average position of the teacher as the position of the sound source. The hall radius (see section 2.2.4.4) describes the minimum distance between the source and receiver positions. Using a directivity factor of 2 (for the human voice), the hall radius varied between 1.27 m and 4.15 m across the measured rooms. The height of the analyser was set to 1.2 m to correspond with an average ear height of a sitting pupil, and a minimum of 1 m distance to reflecting surfaces like walls and desks was used. Following these guidelines, the analyser most often ended up in the back or along the sides of the classrooms.

Placing the analyser in the reverberation field when considering the pupils as sound sources is more difficult. It would also be non-realistic, as all the pupils normally have several pupils within the hall radius of the room. It is important to include the contribution of direct sound when analysing the activity noise, since this is a substantial factor in the experienced level for the pupils. The importance of direct sound in activity noise has also been highlighted by Bradley and Sato [16].

Room measures and a typical placement of the sound analyser are shown in the floor plan in figure 3.2, with photos from the same room in figure 3.3.

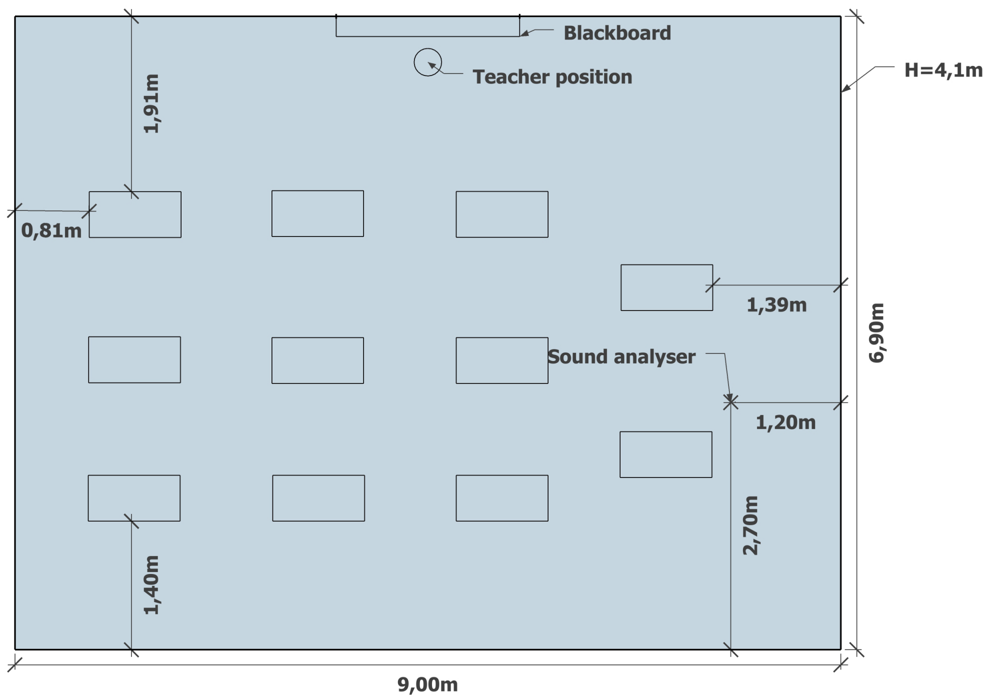

Figure 3.2: Floor plan of one typical enclosed classroom

Figure 3.3: Photos of one typical enclosed classroom (with the floor plan shown in figure 3.2)

3.1.5 Finding average sound pressure level and activity noise level for lectures

Two methods previously used for finding the average SPL and the activity noise level have been compared. These have been used in studies by Shield et al. [5] and Hodgson et al. [4].

3.1.5.1 Method used by Shield et al.

Shield et al.'s method is presenting two separate values from recorded SPL. L_{A90} is used to represent the activity noise level and L_{Aeq} is used to represent the signal (the person speaking) [5]. The method is simple, and some sound analysers can even provide these levels directly in the instrument. Shield et al. measured plenary activities, group work, individual work and watching/listening to video/audio as separate categories. In the comparison with Hodgson et al.'s method, only plenary activity will be studied here.

3.1.5.2 Method used by Hodgson et al.

Hodgson et al. argued that recorded sound pressure levels in university lectures are caused by three categories of sources: ventilation noise, student activity and speech [4]. Thus, by fitting three normal distribution curves to a histogram of recorded SPLs, it should be possible to assign the three curve peaks to those three different sound sources. To be able to compare with Shield et al.'s method, two normal distribution curves have been used to obtain the activity noise, $\mu 1$ and the speech level, $\mu 2$. A typical representation of a lecture with Hodgson et al.'s method is shown in figure 3.4. Hodgson et al. did not measure any other activities than plenary activities.

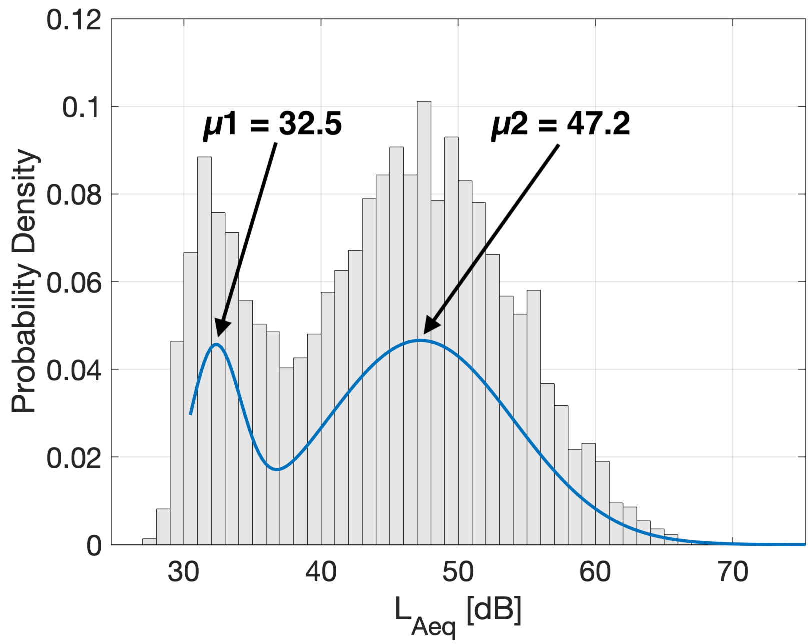

Figure 3.4: Histogram of recorded SPL during 14 min 42 sec of plenary activity. $\mu 1$ and $\mu 2$ represents the activity noise level and the speech level respectively.

3.1.5.3 Comparison of Shield et al.'s and Hodgson et al.'s methods

Shields et al.'s method is the easiest to use due to the required post-processing of recorded levels with Hodgson et al.'s method. It is therefore of interest to compare the two methods. Figure 3.5 shows the activity noise components, L_{A90} and $\mu 1$ and the average SPL L_{Aeq} and $\mu 2$ from plenary sequences from the measured data set. Sequences of 80 seconds or shorter duration are excluded. Both comparisons are significantly correlated (($r = 0.80$, $p < 0.01$) and ($r = 0.82$, $p < 0.01$) respectively).

The correlation favours Shield et al.'s method, since L_{A90} is an easier parameter to calculate. However, one should be aware that the values are correlated, but not equal. There is a

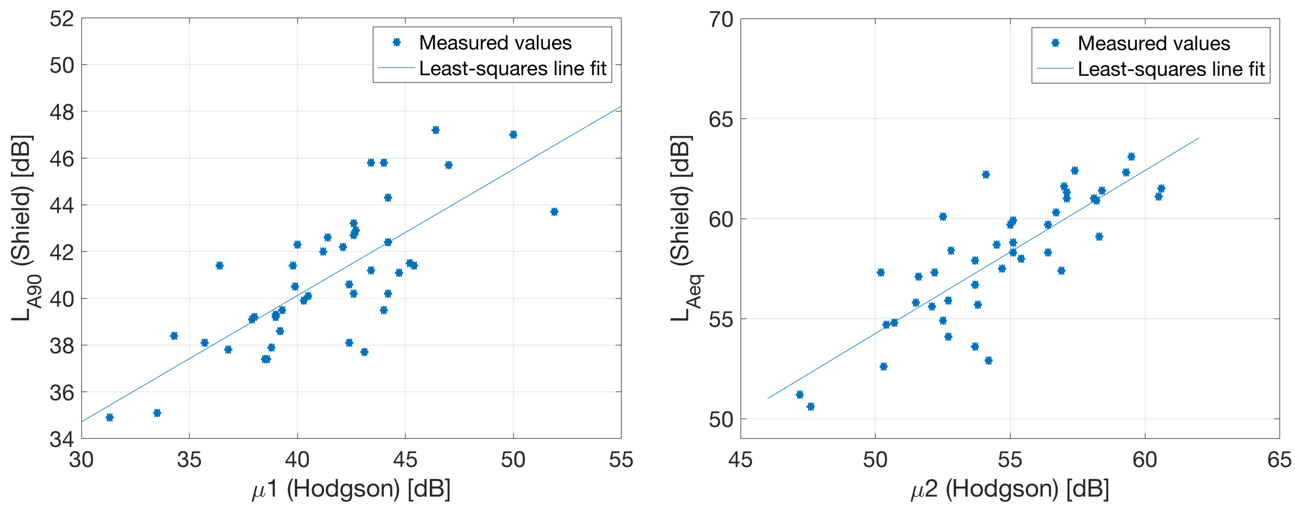

Figure 3.5: Comparison of Shield- and Hodgson method

deviation between the line fit and many of the measured values, meaning that L_{A90} and $\mu 1$ or L_{Aeq} and $\mu 2$ will not have the same value.

3.2 Measuring room acoustics

Two parameters of room acoustics is mentioned in in the Norwegian building regulation for classrooms, NS 8175:2012: reverberation time and background noise [1]. Background noise is here including technical noise from ventilation systems, but not from AV equipment. In the current study, both these parameters were measured in unoccupied classrooms during breaks.

3.2.1 Reverberation time

The reverberation time was recorded using a paper bag as excitation signal. The paper bag was blown in the average teacher position three times with the sound analyser placed in a new position for each blow. The method was chosen due to the need for a fast and efficient measurement during breaks between lessons.

Compared to methods described in ISO 3382-2:2008 [9], the paper bag method can be considered a simplified method. During the pilot measurements for the project, a comparison between the paper bag method and a precision method from ISO 3382 was carried out in a room with comparable size to a normal enclosed classroom. The precision method used 2 source positions and 6 receiver positions, a total of 12 combinations. Guidelines from ISO 3382 were followed regarding positioning at least 1 m from room boundaries and 2 m between receiver positions. Also, symmetry was avoided in the positioning. The integrated impulse response method was chosen as excitation signal. A logarithmic sine sweep from 40

Hz to 20.000 Hz was conducted twice and then averaged for each source/receiver position. An omni-directional loudspeaker and a free-field microphone was used to record the room response. T_{20} was registered in 1/3 octave bands, and each frequency band was averaged between the 12 source/receiver combinations.

Figure 3.6 shows the mean value and the 95% confidence interval for T_{20} measured with the precision method and the simplified method. It is observed that the measurements mostly follow each other closely above 200 Hz. The comparison also holds for T_{mf}, which looks at the 500, 1000 and 2000 Hz frequency bands. T_{mf} was used in the study by Shield et al. [5].

It is observed that the confidence intervals mostly overlap, both for the individual frequency bands and T_{mf}, indicating that the simplified method can be a valid measurement method.

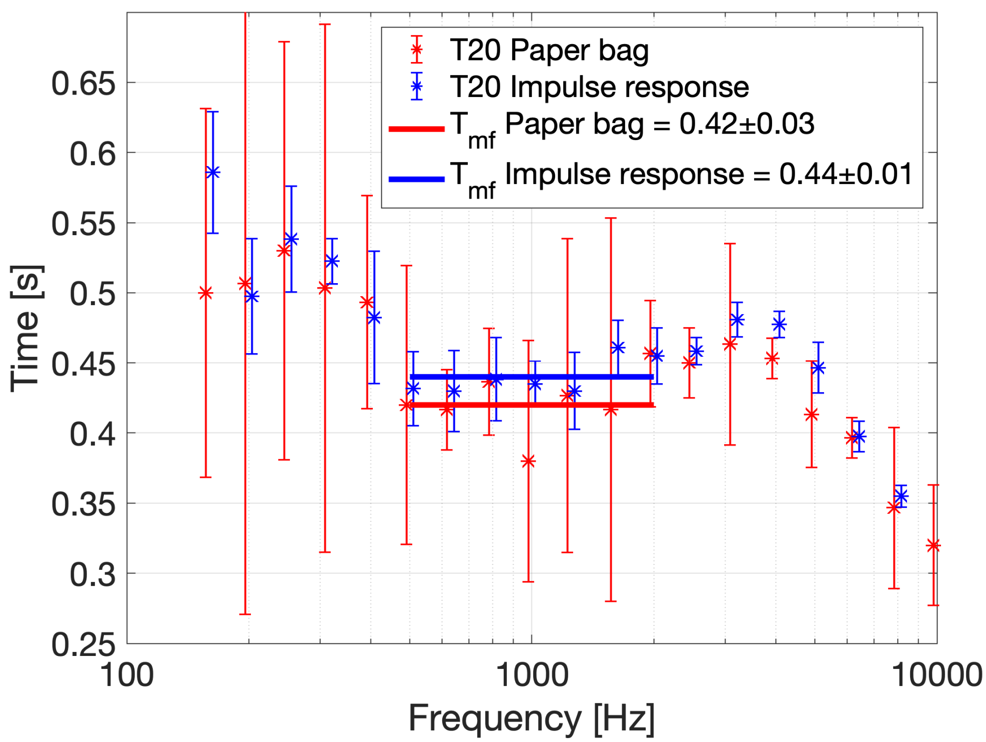

Figure 3.6: Mean T_{20} in 1/3 frequency bands and T_{mf} with 95% confidence intervals. Comparison between simplified paper bag method and precision impulse response method

3.2.2 Background noise

Background noise, as defined in NS 8175, puts some requirements to the measurement situation. Ideally, one would do the measurement with no other people present in the building, and no traffic or noise from outside the building. For this study, background noise was measured during breaks in the school day. A similar method of background noise measurement was used by Shield et al. and defined as the unoccupied ambient noise level [5]. The aim was to record levels that were also present in the lecture time. Newer buildings are very well sound insulated, whereas older are more vulnerable to noise from other rooms or from the outside. The older buildings were difficult to measure, due to raised noise levels from hallways and school yard during breaks. However, it was possible to find times when measurements were possible, either with measuring an empty classroom during lecture time (if the class was using a different room), or by making sure that neighbouring rooms and the school yard outside was empty during a break. One should be aware that this method makes the measured background noise levels unsuitable for studying whether the rooms comply with the limits in NS 8175.

As for the reverberation time measurement, three receiver positions were used during background noise measurement. For each position, a 15 seconds interval was recorded with fast time-weighting, and the equivalent noise level, L_{eq}, was output with 125 ms sample time in 1/3 octave bands. The background noise level was recorded both with and without AV equipment turned on.

Background noise levels were A-weighted prior to the analysis. For each separate classroom, the level given here is the average A-weighted sound pressure level, L_{Aeq}, of the three separate measurements.

3.2.3 Room dimensions

Width, length and height were measured with a laser distance meter. Some rooms were non-rectangular or had different heights. Here, the measures are registered as the most representative in the area where the pupils were seated. The room volume was found from the entire space.

In open-plan spaces the volume is calculated for the entire space, including areas where other groups had their lectures. However, the width, length and height was registered for the area where the measured lecture was taken place. The maximum distance between the average teacher position and a pupil position was also measured and registered in both room types.

3.2.4 Other room acoustic parameters

Other room acoustic parameters were calculated from the reverberation time and the room volume. These are the absorption area, A (equation 2.4), hall radius, r_h (equation 2.11), using a directivity factor of 2, the acoustic capacity, N_{max} (equation 2.18) and the mean room strength, G_{mean} (equation 2.14) using the closest position, r_1 as 1.5 m and r_2 = maximum distance. Finally, the acoustic utilisation ratio, $N_{utilisation}$, was found for each room using equation 2.19.

3.3 Statistical analysis

To analyse correlation between sound levels and room design, the corr-function in Matlab was used. This function returns the linear correlation coefficient, r_s, and the level of statistical significance, p_s, when given two sets of measurements, e.g. reverberation time and activity noise. The regression-function was also used to find the linear regression coefficients, $\hat{\alpha}$ and $\hat{\beta}$, for a function connecting two variables.

3.4 Selection of schools

Trondheim has 40 schools that includes 5th to 7th grade, and 20 of the schools were approached for this study. Some did not reply, a few refused to participate and 8 ended up being measured. Even though 20% of the schools were measured, the schools are used by approximately 25% of the pupils in the age group. The schools are both open-plan schools and schools with traditional classrooms, and the age of the buildings vary from 1 to 104 years. An overview of the schools is presented in table 3.1.

School name	**Building year**	**Grades**	**Pupils**	**School type**
Brundalen skole	1973	1-7	439	Mixed
Charlottenlund barneskole	1964	1-7	670	Mixed
Ila skole	1921	1-7	392	Enclosed classrooms
Lade skole	2018	1-10	591	Enclosed classrooms
Singsaker skole	1915	1-7	405	Enclosed classrooms
Steindal skole	1979	1-7	366	Open plan
Utleira skole	1997	1-7	466	Open plan
Åsveien skole og ressurssenter	2015	1-10	589	Enclosed classrooms

Table 3.1: Schools where measurements were conducted

In total, 40 lectures were measured, 22 teachers were involved, and the lectures took place in 20 different classrooms or open-plan areas. Two days (approx. 8 AM-2 PM) were spent on each school, giving a total of 16 days with measurements. This resulted in approximately

36 hours of recorded data. 18% of the data was removed due to interruptions or non-educational activities, resulting in approximately 28 hours of data for further analysis. The data was distributed between grades and subjects as shown in figure 3.7, and between schools as shown in figure 3.8.

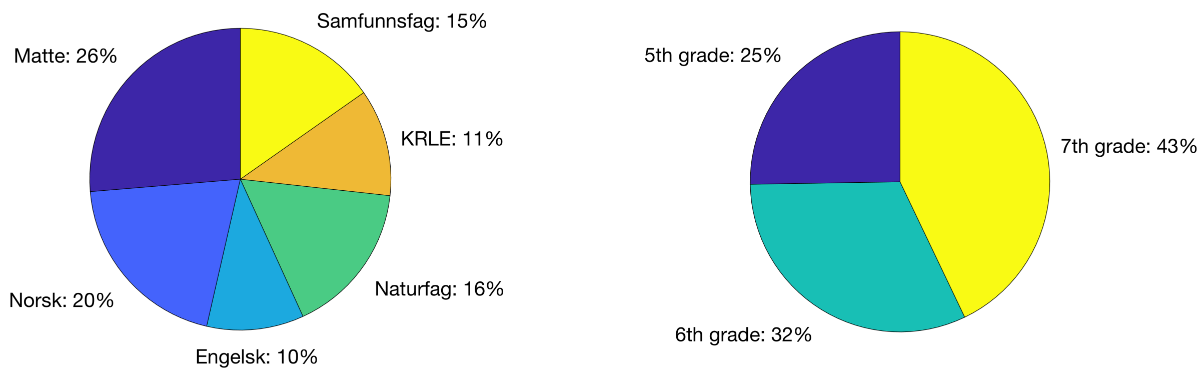

Figure 3.7: Time distribution of subjects and grades

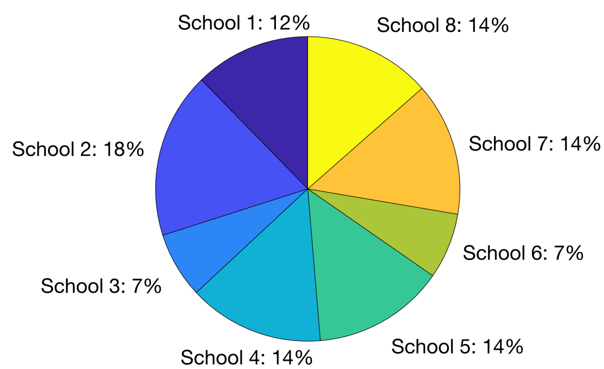

Figure 3.8: Time distribution between schools

3.5 Rooms

Both open-plan areas and enclosed classrooms were measured. Open-plan areas are normally larger than enclosed classrooms and occupied by more pupils. Two to four different lectures can be held in the same area, but usually partial barriers are introduced to reduce sound from travelling between areas. Enclosed classrooms are obviously better isolated from noise from other lectures, but noticeable contributions from neighbouring rooms could occur where the sound insulation was poor.

For the analysis of correlations between parameters, open-plan areas and enclosed classrooms are studied separately due to the differences in size and how they are used. The study contains more data from enclosed classrooms (70% of the rooms and 66% of the time) than open-plan spaces.

3.6 Educational activities

As mentioned in section 1.3, all measured sound levels of this study are sorted for activity. Across all lectures, the background noise, activity noise and average SPL of 118 sequences of different activities were registered. These include 44 plenary sequences, 31 individual work sequences, 15 group work sequences and both film and practical activities have 8 sequences each. When the same activity occurred multiple times in a lecture, it was collected into one sequence. The only activity appearing in all lectures was the plenary activity. It was observed that there were 44 sequences for 40 lectures. The higher number of sequences is explained by some lectures being divided into several recordings due to technical reasons.

Different activities have different optimum acoustic designs. The distribution of activities is therefore an interesting measure. Figure 3.9 and 3.10 show the distribution of activities.

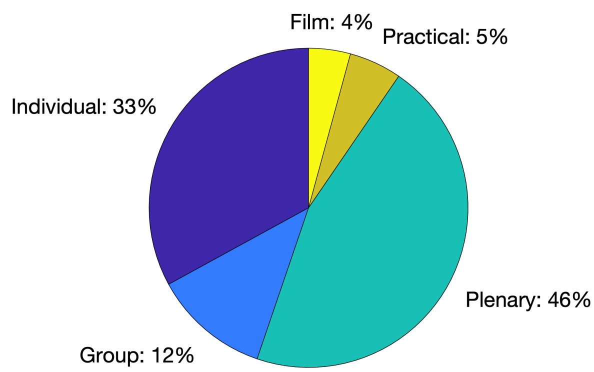

Figure 3.9: Time distribution of activities in lectures

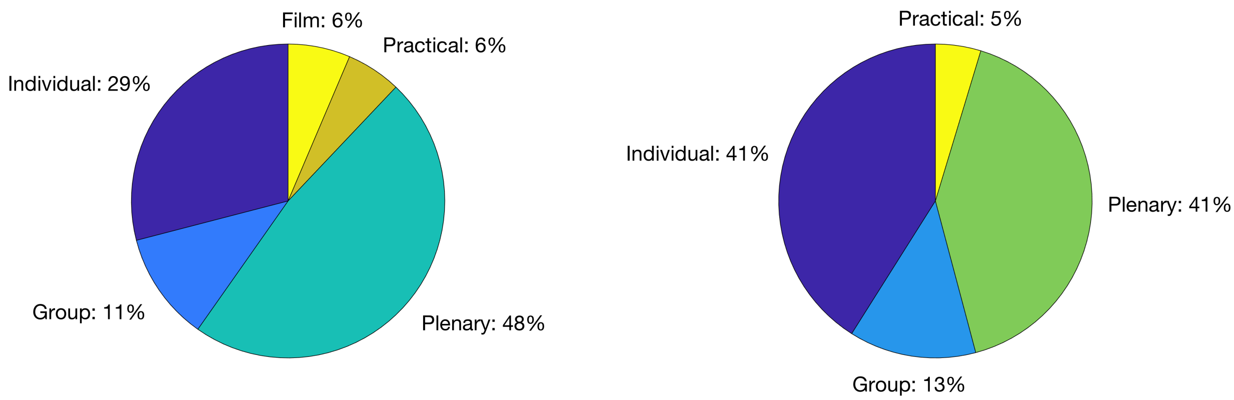

Figure 3.10: Time distribution of activities, enclosed classrooms (left), open-plan spaces (right)

4 Results

This chapter presents the results from measurements and analysis. First, a section on measurements of room dimensions and unoccupied room acoustics is given. Analysis of how reverberation time and background noise correlate with the rooms' dimensions is included here. Further, activity noise, speech level and signal-to-noise ratio in plenary activities are presented. This is followed by results on the average sound pressure level, L_{Aeq}, in individual- and group work. The sound- and noise levels' correlation with room dimensions and room acoustics will be analysed for all these activities. Linear regression and scatter plots will be provided for selected variables and variables that are statistically significantly correlated. Finally, average sound levels from film and practical work is presented. Correlation with other parameters will not by analysed here due to a low sample size. A further discussion of the results, see chapter 5.

4.1 Unoccupied rooms and acoustics

In the study, 20 classrooms were measured. Out of them, 14 enclosed classrooms and 6 open-plan spaces. Table 4.1 and 4.2 show the dimensions, the unoccupied mid-frequency reverberation time, T_{mf}, and the unoccupied background noise with AV-equipment both turned on and off for each room. Results from individual schools are anonymised, and the school numbers do not match the order in table 3.1. The mean values and 95% confidence interval are also included in the bottom of each table. As mentioned in section 3.2.3, width, length and height in open-plan spaces defines the area where the pupils in the lecture that was followed was placed, whereas the room volume is of the entire space.

The background noise with AV turned on is normally higher than with AV turned off, but it is also equal in some rooms. These rooms use a screen for displaying video, eliminating the fan noise from the video projector. One of the open-plan spaces have a lower noise level when AV is turned on. The measurement situation was more difficult to control in open-plan spaces due to multiple entrances and large areas. Measurements can possibly have been affected by events that were not perceived by the observer.

School	**Room**	**Width [m]**	**Length [m]**	**Height [m]**	**Volume [m^3]**	**T_{mf} [s]**	**A-weighted background noise [dB]**	**A-weighted background noise + AV [dB]**
1	1	9	6.9	4.1	255	0.51	28.2	28.2
1	2	9	6.8	4.1	251	0.47	26.1	26.1
1	3	9	6.9	4.1	255	0.49	27.5	27.5
3	1	9.2	12.3	3	382	0.45	32.1	34.9
4	1	6.8	9.1	2.8	206	0.82	39.2	39.7
4	3	9.1	8.3	2.6	260	0.67	38.1	38.8
5	1	6.4	8.7	3.5	172	0.58	27.7	32.0
5	2	6.4	9.8	3.6	226	0.53	34.8	34.8
5	3	6.4	16.3	3.6	376	0.57	31.7	32.4
7	1	6.5	9.5	3.9	231	0.63	34.4	34.4
7	2	9.5	6.4	3.9	228	0.64	37.4	38.2
8	1	9	6.1	3.4	187	0.39	22.2	26.5
8	2	9	6.1	3.4	187	0.40	23.5	27.0
8	3	9	6	3.4	184	0.39	26.1	27.9
Mean		8.2±0.7	8.5±1.7	3.5±0.3	243±37	0.54±0.07	33.6±3.2	34.4±2.8

Table 4.1: Enclosed classrooms: dimensions and unoccupied reverberation time/background noise

School	**Room**	**Width [m]**	**Length [m]**	**Height [m]**	**Volume [m^3]**	**T_{mf}**	**A-weighted background noise [dB]**	**A-weighted background noise + AV [dB]**
2	1	8.3	18.9	3.0	1600	0.37	30.9	31.8
2	2	11.7	25.4	3.8	1600	0.42	30.8	30.0
3	1	10.8	10.8	2.7	613	0.52	35.7	37.2
4	1	6.9	9.3	2.8	373	0.50	35.8	37.9
6	1	9.4	6.4	3.4	817	0.62	32.2	32.2
6	2	9.0	6.4	3.4	817	0.62	30.9	30.9
Mean		9.4±1.8	12.9±8.1	3.2±0.4	970±540	0.51±0.11	33.3±2.5	34.5±3.6

Table 4.2: Open-plan spaces: dimensions and unoccupied reverberation time/background noise

Table 4.3 shows the correlation between reverberation time/background noise and room dimensions. Significant correlation is found between reverberation time and length in open-plan spaces ($r_s = -0.86$, $p_s = 0.03$), meaning a lower reverberation time is to be expected for increasing length of classrooms. No other room dimension parameter show significant correlation with unoccupied T_{mf} or background noise. However, some of the relationships are close to being significant, and it could perhaps be useful to collect more data points to determine whether they are significant or not. These are e.g. height and background noise in open-plan spaces ($r_s = -0.78$, $p_s = 0.06$) and room volume and background noise in open-plan spaces ($r_s = -0.79$, $p_s = 0.06$). Lower background noise could be expected for increased height and room volume in these rooms.

	Sample size	Width	Length	Height	Volume
$T_{mf,enclosed}$	n=14	$p_s = 0.09$	$p_s = 0.36$	$p_s = 0.29$	$p_s = 0.96$
$T_{mf,open-plan}$	n=6	$p_s = 0.90$	$\mathbf{p_s = 0.03}$	$p_s = 0.88$	$p_s = 0.14$
Background noise, enclosed	n=14	$p_s = 0.27$	$p_s = 0.19$	$p_s = 0.19$	$p_s = 0.38$
Background noise, open-plan	n=6	$p_s = 0.63$	$p_s = 0.43$	$p_s = 0.06$	$p_s = 0.06$

Table 4.3: Statistical significance (p_s) of correlation between reverberation time/background noise in unoccupied rooms and room dimensions. p_s in bold indicates significant correlation.

For the enclosed classrooms, which should have a reverberation time of maximum 0.5 to be in compliance with NS 8175:2012, it is observed that 8 out of 14 rooms comply with the standard. For open-plan spaces, where the limit is 0.4 seconds, 2 out of 6 rooms comply with the standard. Norway has a lower maximum value for reverberation time and background noise than many other countries. Compared to the results from Shield et al.'s study in England, where the maximum limit for reverberation time is 0.8 s, the values in this study are lower. However, background noise levels seems to be more similar. Table 4.4 shows the values for the mean background noise level and reverberation time in Shield et al.'s study, together with this study's mean background noise level and reverberation time.

	A-weighted background noise [dB] (Shield et.al.)	**A-weighted background noise [dB] (Bolstad)**	**Reverberation time [s] (Shield et.al.)**	**Reverberation time [s] (Bolstad)**
Enclosed classrooms	33.6 ($\sigma = 5.8$)	33.6 ($\sigma = 5.5$)	0.64 ($\sigma = 0.20$)	0.54 ($\sigma = 0.12$)
Open-plan spaces	35.4 ($\sigma = 7.1$)	33.3 ($\sigma = 2.4$)	0.53 ($\sigma = 0.09$)	0.51 ($\sigma = 0.10$)

Table 4.4: Comparison of mean reverberation time and background noise with Shield et al.

4.2 Activity noise, plenary activity

As discussed in section 3.1.5, L_{A90} can be used as a measure of the activity noise. To separate the activity noise generated by pupils from the unoccupied background noise, a background noise correction (introduced in section 3.1.1) has been applied. Figure 4.1 shows the spectrum of the uncorrected and corrected L_{90} and L_{A90} together with the unoccupied background noise for the plenary activity in one single lecture from the study. It is observed that the background noise has a concentration of energy in the lower frequencies. There is also a slight increase from 8 kHz and upwards. Accordingly, the corrected activity noise has the largest correction in the lowest and highest frequencies. However, introducing the A-weighting shown in the right plot of figure 4.1, reveals that the impact of the correction is limited, due to the middle frequencies dominating the spectrum.

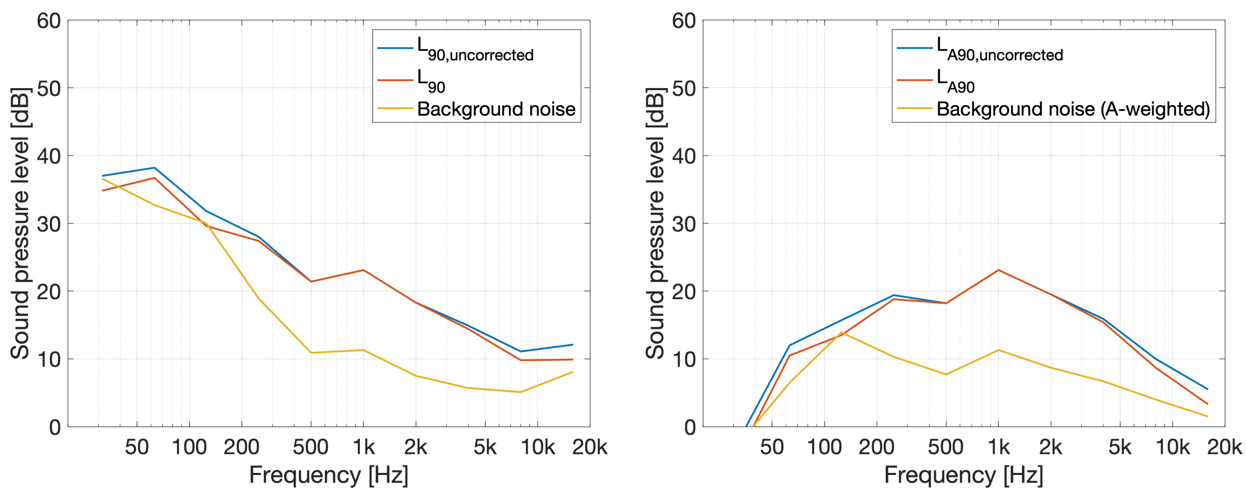

Figure 4.1: Frequency spectrum for uncorrected and corrected activity noise (L_{90}) and unoccupied background noise. The left plot has unweighted levels. The right plot has A-weighted levels.

Figure 4.2 shows the mean value and the 95% confidence interval for L_{A90} for each school in the study. For plenary activity, the sample size is 44, including 31 sequences from enclosed classrooms and 14 from open-plan spaces. It is observed that the range of L_{A90} is from 38.4 dB to 44.9 dB. The mean activity noise level for all plenary sequences on all schools is

$$L_{A90} = 41.3 \pm 0.9 \text{ dB}, \qquad (n = 44) \tag{4.1}$$

L_{A90} can also be given as a level uncorrected for background noise. As suspected from figure 4.1, the level is close to the corrected level.

$$L_{A90,uncorrected} = 41.8 \pm 0.9 \text{ dB}, \qquad (n = 44) \tag{4.2}$$

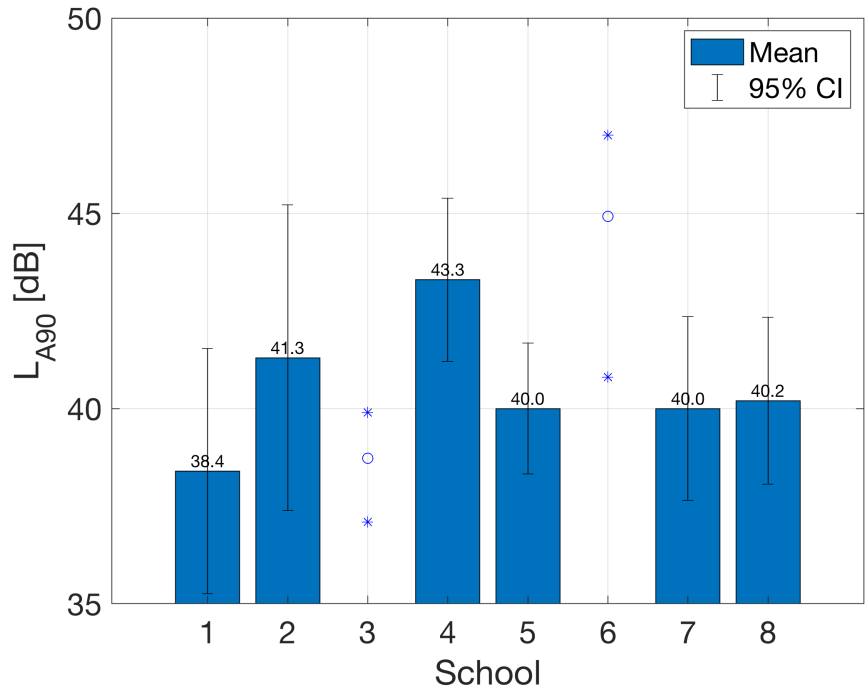

Figure 4.2: Plenary activity: L_{A90} with 95% confidence interval for each school in the study (School 3 and 6 are represented by individual data points (*) and a mean value (o) due to a sample size of 2).

The results for activity noise can further be sorted for enclosed classrooms and open-plan spaces, both corrected for background noise

$$L_{A90,enclosed} = 40.3 \pm 0.9 \text{ dB}, \qquad (n = 30) \tag{4.3}$$

$$L_{A90,open-plan} = 42.9 \pm 2.3 \text{ dB}, \qquad (n = 14) \tag{4.4}$$

4.2.1 Correlation with room dimensions

This section focuses on how the dimensions of the room affects the activity noise during plenary activities. Table 4.5 shows the correlation between L_{A90} and room dimensions.

	Sample size	**Width**	**Length**	**Height**	**Volume**	**Max dist.**
$L_{A90,enclosed}$	n=30	$p_s = 0.38$	$p_s = 0.59$	$\mathbf{p_s = 0.02}$	$p_s = 0.80$	$p_s = 0.86$
$L_{A90,open-plan}$	n=14	$\mathbf{p_s = 0.03}$	$\mathbf{p_s = 0.03}$	$p_s = 0.08$	$p_s = 0.14$	$\mathbf{p_s = 0.03}$

Table 4.5: Statistical significance (p_s) of correlation between activity noise (L_{A90}) and room dimensions. p_s in bold indicates significant correlation (Plenary activity).

For enclosed classrooms, L_{A90} shows a significant correlation with room height from the data set in this study ($r_s = -0.44$, $p_s = 0.02$), with increasing height leading to lower activity noise. However, correlation with height is not observed for open-plan spaces. No correlation is observed for other dimension parameters of enclosed classrooms, but for open-plan spaces, width ($r_s = -0.59$, $p_s = 0.03$), length ($r_s = -0.57$, $p_s = 0.03$) and the maximum distance between the teacher and a pupil position ($r_s = -0.59$, $p_s = 0.03$) is significantly correlated to L_{A90}. The correlations in open-plan spaces between activity noise and dimensions will not be emphasised for the plenary activity, as the pupils were mostly gathered in a listening circle around the teacher during this activity, meaning that only a small amount of the area was used.

The r_s-values indicate that there is some spread in the measured data, even though the correlation is significant. Figure 4.3 shows the measured values for L_{A90} with respect to room height in both room types.

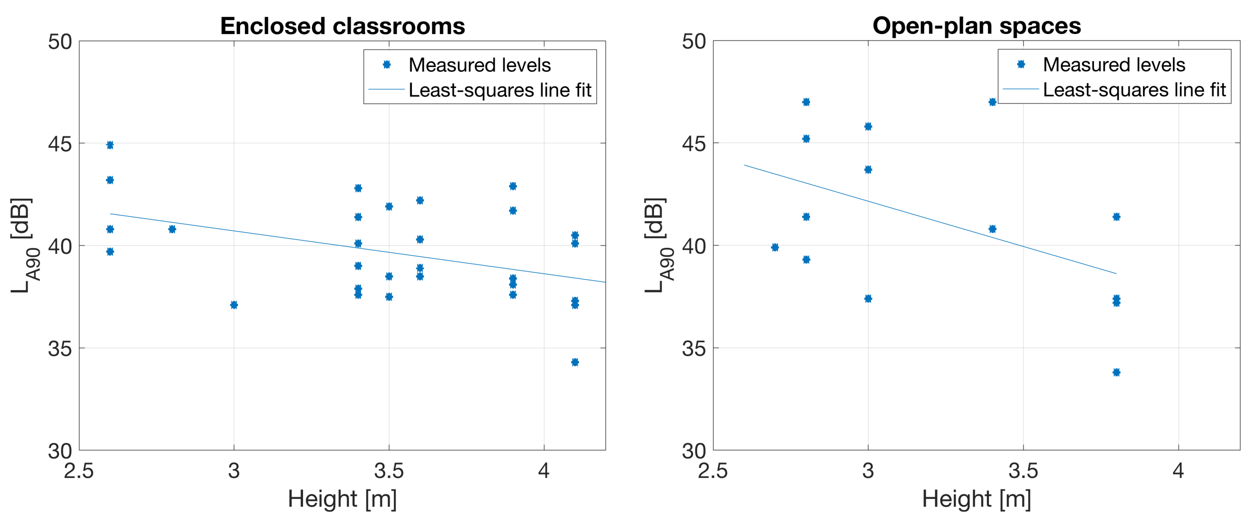

Figure 4.3: L_{A90} with respect to room height (Plenary activity).

Linear regression provides the following expression for activity noise as a function of height in enclosed classrooms.

$$L_{A90} = 47.0 - 2.1 \cdot h \text{ [dB]} \tag{4.5}$$

4.2.2 Correlation with room acoustics

Table 4.6 shows the p_s-values for correlation between activity noise, L_{A90}, and room acoustic parameters.

One could expect the activity noise to correlate with T_{mf} and background noise. Significant correlation for these relationships were found in Shield et al.'s study, and through their presence in the building standards, reverberation time and background noise are important parameters to consider. However, as shown in table 4.6, neither background noise nor T_{mf} are significantly correlated to L_{A90}. There is not a significant correlation with absorption area, hall radius or G_{mean} either.

	Sample size	T_{mf}	Back-ground noise	A	Hall radius	G_{mean}
$L_{A90,enclosed}$	n=30	$p_s = 0.16$	$p_s = 0.20$	$p_s = 0.23$	$p_s = 0.24$	$p_s = 0.25$
$L_{A90,open-plan}$	n=14	$p_s = 0.27$	$p_s = 0.29$	$p_s = 0.18$	$p_s = 0.16$	$p_s = 0.14$

Table 4.6: Statistical significance (p_s) of correlation between activity noise (L_{A90}) and room acoustic parameters (Plenary activity).

Figure 4.4 shows activity noise with respect to background noise and reverberation time for both enclosed classrooms and open-plan spaces.

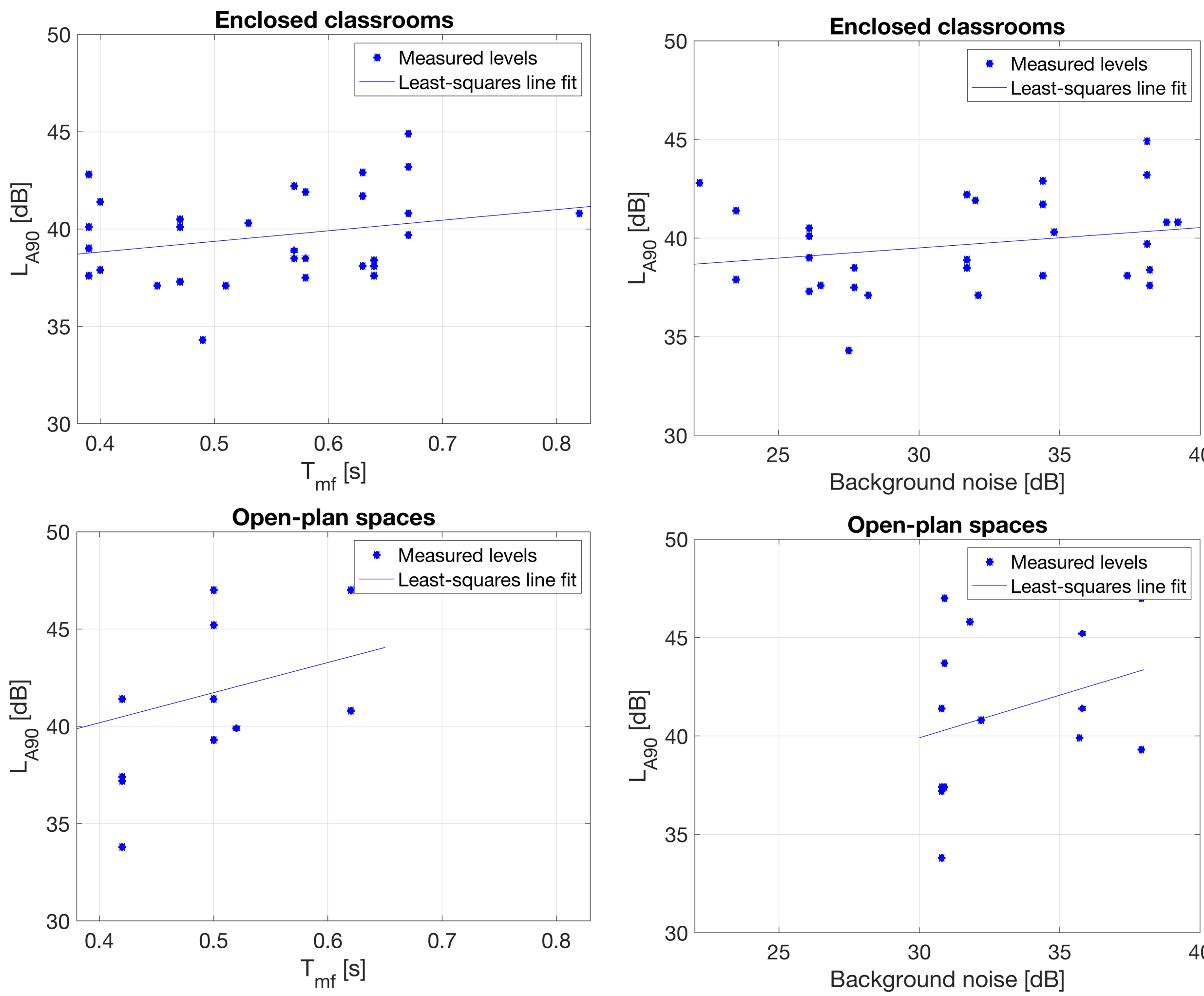

Figure 4.4:
Top: L_{A90} with respect to T_{mf} ($r_s = 0.26$, $p_s = 0.16$) and background noise ($r_s = 0.24$, $p_s = 0.20$), enclosed classrooms.
Bottom: L_{A90} with respect to T_{mf} ($r_s = 0.32$, $p_s = 0.27$) and background noise ($r_s = 0.30$, $p_s = 0.29$), open-plan spaces
(Plenary activity).

4.2.3 Correlation with room occupancy

Table 4.7 shows the p_s-values for correlation between L_{A90} and room occupancy. For the occupancy, there was no large variation between the lectures. The mean number of pupils was 22 ± 2. However, the acoustic capacity had larger variations, and the acoustic utilisation ratio describes the occupancy with respect to the acoustic capacity. For open-plan spaces, occupancy describes the number of pupils in the lecture that was followed, not the total number of pupils in the entire space. It would be useful to have data of the total occupancy, but this was not realised during measurements.

	Sample size	**No.people**	**Acoustic utilisation ratio**
$L_{A90,enclosed}$	n=30	$p_s = 0.54$	$\mathbf{p_s = 0.03}$
$L_{A90,open-plan}$	n=14	$p_s = 0.83$	$p_s = 0.20$

Table 4.7: Statistical significance (p_s) of correlation between activity noise (L_{A90}) and room occupancy. p_s in bold indicates significant correlation (Plenary activity).

The activity noise level, L_{A90}, seems to be significantly correlated with the acoustic utilisation ratio ($r_s = 0.39$, $p_s = 0.03$) in enclosed rooms. Again, the r_s-value indicates some spread in the data set, but a positive correlation is observed, meaning that higher activity noise levels can be expected for rooms with higher occupancy relative to the acoustic capacity. The measured levels of L_{A90} with respect to N_{ratio} are shown in figure 4.5.

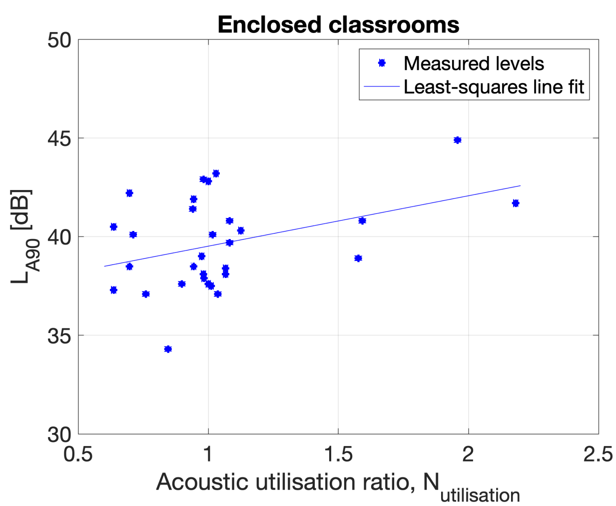

Figure 4.5: L_{A90} with respect to N_{ratio} in enclosed classrooms (Plenary activity).

Removing rooms with $N_{ratio} > 1.5$ results in no significant correlation between L_{A90} and $N_{utilisation}$ ($r_s = 0.11$, $p_s = 0.58$).

4.2.4 Correlations using Hodgson et al.'s method for activity noise

To check if the correlation between Hodgson et al.'s- and Shield et al.'s method holds (see section 3.1.5.3), correlation was also tested between the room dimensions and $\mu1$ with Hodgson et al.'s method. As for L_{A90}, $\mu1$ also correlates with room height ($r_s = -0.36$, $p_s = 0.05$) for enclosed classrooms. Unlike for L_{A90}, no significant correlation is found between $\mu1$ and width or length in open-plan spaces. However, like L_{A90}, $\mu1$ is also significantly correlated to maximum teacher-to-pupil distance in open-plan spaces ($r_s = -0.54$, $p_s = 0.05$). Further, no significant correlations are found between $\mu1$ and room acoustics or occupancy. Unlike L_{A90}, $\mu1$ does not correlate significantly with the acoustic utilisation ratio in enclosed classrooms.

4.3 Speech level, plenary activity

The average sound pressure level, L_{Aeq}, can be used as a measure of the speech level in plenary activities. Figure 4.6 shows the spectrum of the three level components, L_{eq}, L_{90} and unoccupied background noise for the plenary activity in one single lecture from the study. As shown in the left plot, the components have similar levels for the lower frequencies, but from 100 Hz and upwards, they are more separated. Again, the A-weighting shown in the right plot indicates that the lower frequencies have a limited impact on the single-value level.

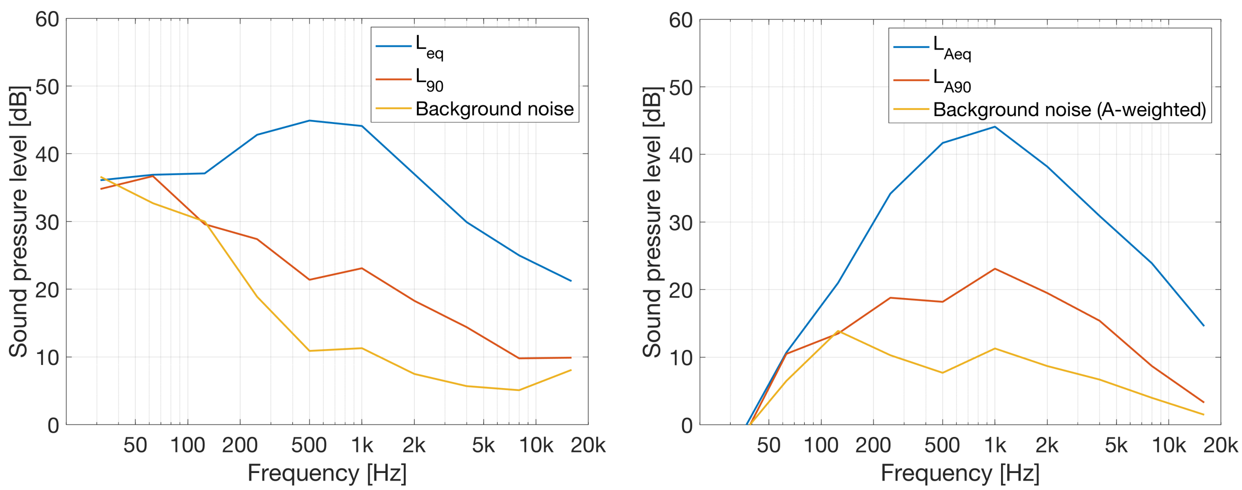

Figure 4.6: Frequency spectrum for speech, activity noise and background noise

Figure 4.7 shows the mean value and the 95% confidence interval for L_{Aeq} for each school in this study. It is observed that the range of L_{Aeq} is from 54.7 dB to 61.6 dB. The average sound pressure level, L_{Aeq}, for all plenary sequences on all schools is

$$L_{Aeq,plenary} = 59.0 \pm 1.0 \text{ dB}, \qquad (n = 44) \tag{4.6}$$

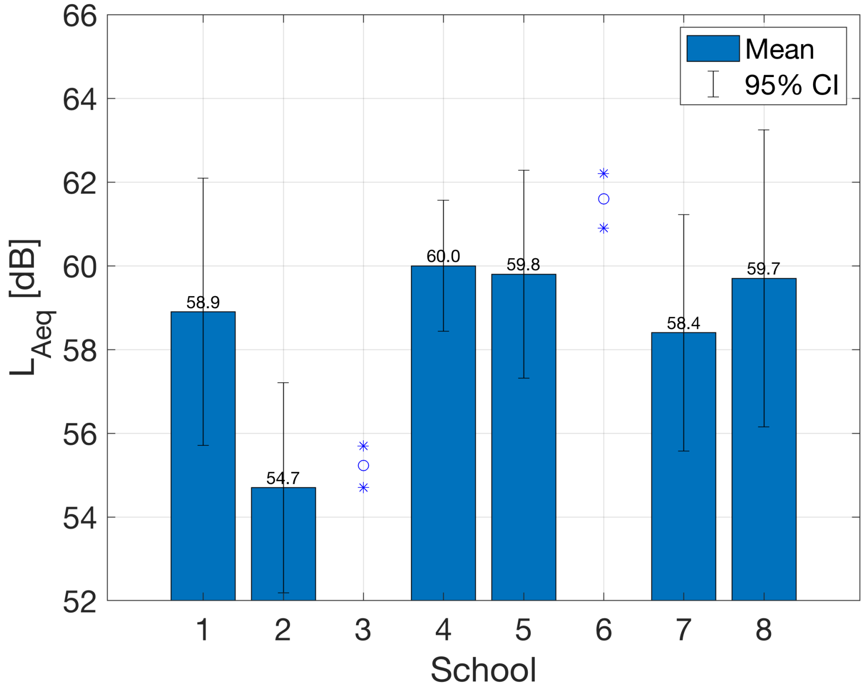

Figure 4.7: Plenary activity: L_{Aeq} with 95% confidence interval for each school in the study (School 3 and 6 are represented by individual data points (*) and a mean value (o) due to a sample size of 2).

L_{Aeq} can also be given separately for enclosed classrooms and open-plan spaces

$$L_{Aeq,plenary,enclosed} = 59.4 \pm 1.0 \text{ dB}, \qquad (n = 30) \tag{4.7}$$

$$L_{Aeq,plenary,open-plan} = 57.9 \pm 2.1 \text{ dB}, \qquad (n = 14) \tag{4.8}$$

4.3.1 Correlation with room dimensions

Table 4.8 shows the p_s-values for the correlation between L_{Aeq} and the room dimensions.

	Sample size	**Width**	**Length**	**Height**	**Volume**	**Max dist.**
$L_{Aeq,enclosed}$	n=30	$p_s = 0.17$	$p_s = 0.66$	$p_s = 0.18$	$p_s = 0.61$	$p_s = 0.59$
$L_{Aeq,open-plan}$	n=14	$p_s = 0.05$	$\mathbf{p_s < 0.01}$	$p_s = 0.23$	$\mathbf{p_s = 0.02}$	$\mathbf{p_s < 0.01}$

Table 4.8: Statistical significance (p_s) of correlation between speech level (L_{Aeq}) and room dimensions. p_s in bold indicates significant correlation (Plenary activity).

No significant correlations are found for enclosed classrooms, but for open-plan spaces, length ($r_s = -0.75$, $p_s < 0.01$), volume ($r_s = -0.61$, $p_s = 0.02$) and maximum teacher-pupil distance ($r_s = -0.79$, $p_s < 0.01$) are significantly correlated to L_{Aeq}. These are the same correlations that were observed for L_{A90} in open-plan spaces, except that correlation with room volume was not found for L_{A90}. One should remember that most plenary activities were conducted with the pupils gathered in a listening circle in the open-plan spaces. This means that the pupils are not spread over the entire area, but rather within the direct field of the teacher. Therefore, the correlations discovered here will not be emphasised.

4.3.2 Correlation with room acoustics and noise

Table 4.9 shows the p_s-values for the correlation between L_{Aeq} and the room acoustic parameters. It is observed that L_{Aeq} is significantly correlated to activity noise (L_{A90}) in both enclosed classrooms ($r_s = 0.55$, $p_s < 0.01$) and open-plan spaces ($r_s = 0.76$, $p_s < 0.01$). L_{Aeq} is plotted with respect to L_{A90} in figure 4.8, and shows that the Lombard effect is present in the classrooms. For increasing activity noise, the person speaking raises the speech level.

	Sample size	$\mathbf{T_{mf}}$	**Background noise**	$\mathbf{L_{A90}}$	**A**	**Hall radius**	$\mathbf{G_{mean}}$
$L_{Aeq,enclosed}$	n=30	$p_s = 0.49$	$p_s = 0.94$	$\mathbf{p_s < 0.01}$	$p_s = 0.35$	$p_s = 0.36$	$p_s = 0.34$
$L_{Aeq,open-plan}$	n=14	$\mathbf{p_s = 0.01}$	$p_s = 0.16$	$\mathbf{p_s < 0.01}$	$\mathbf{p_s = 0.01}$	$\mathbf{p_s = 0.01}$	$\mathbf{p_s = 0.01}$

Table 4.9: Statistical significance (p_s) of correlation between speech level (L_{Aeq}) and room acoustic parameters or noise. p_s in bold indicates significant correlation (Plenary activity).

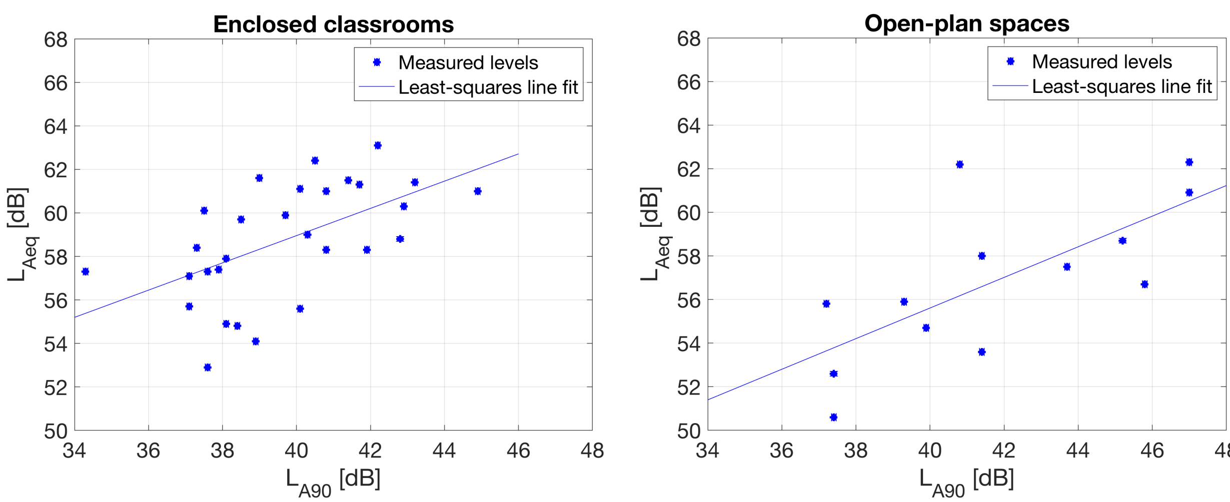

Figure 4.8: L_{Aeq} with respect to L_{A90} (Plenary activity).

Linear regression provides the following equations for L_{Aeq} as a function of L_{A90}.

$$L_{Aeq,enclosed} = 0.63 \cdot L_{A90} + 33.9 \text{ [dB]} \tag{4.9}$$

and

$$L_{Aeq,open-plan} = 0.70 \cdot L_{A90} + 27.5 \text{ [dB]} \tag{4.10}$$

L_{Aeq} also shows significant correlation with T_{mf} ($r_s = 0.68$, $p_s = 0.01$), A ($r_s = -0.64$, $p_s < 0.01$), hall radius ($r_s = -0.64$, $p_s = 0.01$) and G_{mean} ($r_s = 0.65$, $p_s = 0.01$) in open-plan spaces. Here, there is a clear tendency that the speech level is higher when the reverberation increases. L_{Aeq} in both enclosed classrooms and open-plan spaces are plotted as a function of reverberation time (T_{mf}) in figure 4.9

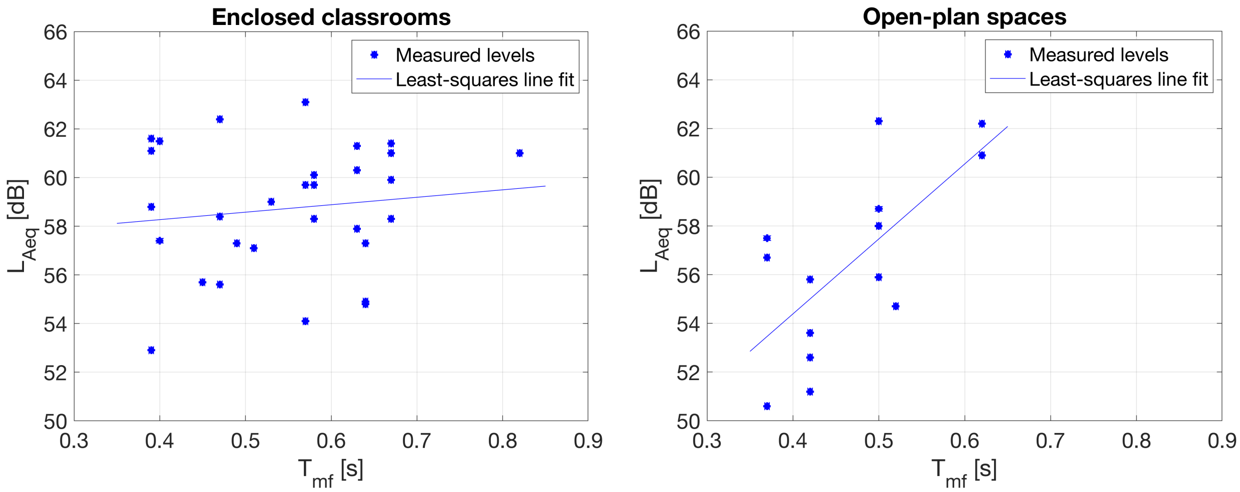

Figure 4.9: L_{Aeq} with respect to T_{mf} in enclosed classrooms and open-plan spaces (Plenary activity).

4.3.3 Correlation with room occupancy

Table 4.10 shows the p_s-values for correlation between L_{Aeq} and room occupancy. Acoustic utilisation ratio in open-plan spaces is the only parameter significantly correlated to L_{Aeq} ($r_s = 0.56$, $p_s = 0.04$), with higher speech level expected for rooms with higher occupancy relative to the acoustic capacity.

	Sample size	**No.people**	**Acoustic utilisation ratio**
$L_{Aeq,enclosed}$	n=30	$p_s = 0.35$	$p_s = 0.69$
$L_{Aeq,open-plan}$	n=14	$p_s = 0.70$	$\mathbf{p_s = 0.04}$

Table 4.10: Statistical significance (p_s) of correlation between speech level (L_{Aeq}) and room occupancy. p_s in bold indicates significant correlation (Plenary activity).

4.4 Signal-to-noise ratio, plenary activity

So far, activity noise level and speech level have been studied separately. It is also possible to look at these levels combined. The signal-to-noise ratio, SNR, in plenary activities is the deviation between L_{Aeq} and the sum of background noise and activity noise, $L_{A90,uncorrected}$. SNR is valuable for predicting speech intelligibility. From the measured schools in this study, the following SNR has been found

$$SNR_{enclosed} = 19.0 \pm 0.9 \text{ dB}, \quad (n = 30) \tag{4.11}$$

$$SNR_{open-plan} = 15.5 \pm 1.5 \text{ dB}, \quad (n = 14) \tag{4.12}$$

4.4.1 Correlation with room dimensions

Table 4.11 shows the p_s-values for SNR and room dimensions. No room dimensions are significantly correlated to SNR, but room height is close to being significantly correlated ($r_s = 0.36$, $p_s = 0.05$).

	Sample size	**Width**	**Length**	**Height**	**Volume**	**Max dist.**
$SNR_{enclosed}$	n=30	$p_s = 0.14$	$p_s = 0.07$	$p_s = 0.05$	$p_s = 0.37$	$p_s = 0.06$
$SNR_{open-plan}$	n=14	$p_s = 0.20$	$p_s = 0.63$	$p_s = 0.59$	$p_s = 0.93$	$p_s = 0.33$

Table 4.11: Statistical significance (p_s) of correlation between SNR and room dimensions (Plenary activity).

4.4.2 Correlation with room acoustics

Table 4.12 shows the p_s-values for SNR and room acoustic parameters. Only unoccupied background noise in enclosed classroom is significantly correlated to SNR ($r_s = -0.45$, $p_s = 0.01$) with increasing background noise leading to lower SNR.

	Sample size	$\mathbf{T_{mf}}$	**Bakcground noise**	$\mathbf{L_{A90}}$	**A**	**Hall radius**	$\mathbf{G_{mean}}$
$SNR_{enclosed}$	n=30	$p = 0.27$	$\mathbf{p = 0.01}$	$\mathbf{p < 0.01}$	$p = 0.88$	$p = 0.98$	$p = 0.94$
$SNR_{open-plan}$	n=14	$p = 0.87$	$p = 0.96$	$\mathbf{p < 0.01}$	$p = 0.96$	$p = 0.99$	$p = 0.91$

Table 4.12: Statistical significance (p_s) of correlation between SNR and room acoustic parameters. p_s in bold indicates significant correlation (Plenary activity).

No correlations with background noise was found for L_{A90} or L_{Aeq} individually, but combining these levels, it is observed that background noise has an impact. Hence, background noise is likely to affect speech intelligibility in enclosed classrooms. Figure 4.10 shows SNR with respect to background noise in enclosed classrooms. Also, SNR with respect to reverberation time is shown, even though these parameters are not significantly correlated.

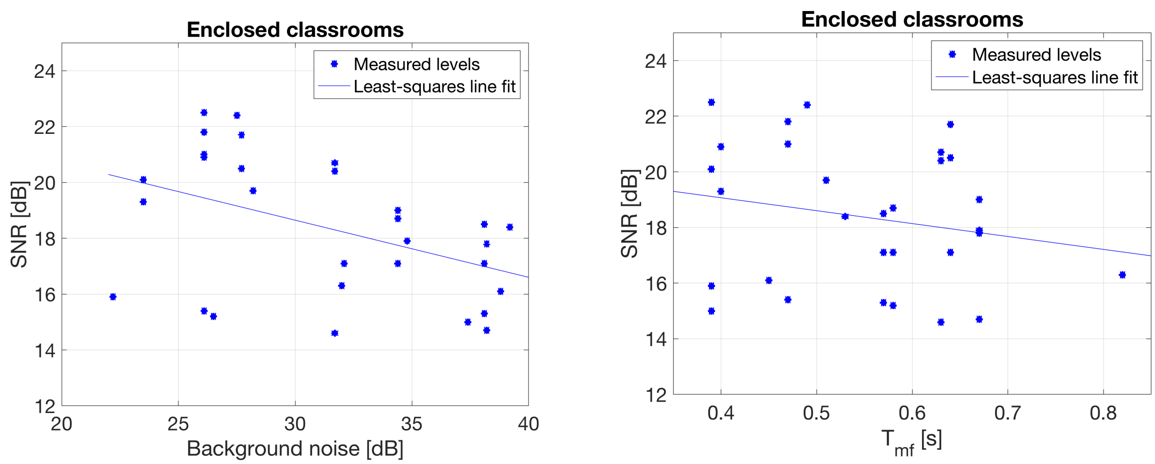

Figure 4.10: SNR with respect to background noise and reverberation time in enclosed classrooms (Plenary activity).

Linear regression provides the following equation for SNR as a function of background noise

$$SNR = 24.8 - 0.2 \cdot L_{backgroundnoise} \text{ [dB]} \tag{4.13}$$

4.4.3 Correlation with room occupancy

Table 4.13 shows the p_s-values for SNR and occupancy. SNR is significantly correlated to the acoustic utilisation ratio ($r_s = -0.44$, $p_s = 0.01$), with a decreasing SNR for rooms with higher occupancies relative to the acoustic capacity. SNR with respect to acoustic utilisation ratio is shown in figure 4.11.

	Sample size	**No.people**	**Acoustic utilisation ratio**
$L_{Aeq,enclosed}$	n=30	$p_s = 0.05$	$\mathbf{p_s = 0.01}$
$L_{Aeq,open-plan}$	n=14	$p_s = 0.16$	$p_s = 0.78$

Table 4.13: Statistical significance (p_s) of correlation between SNR and room occupancy. p_s in bold indicates significant correlation (Plenary activity).

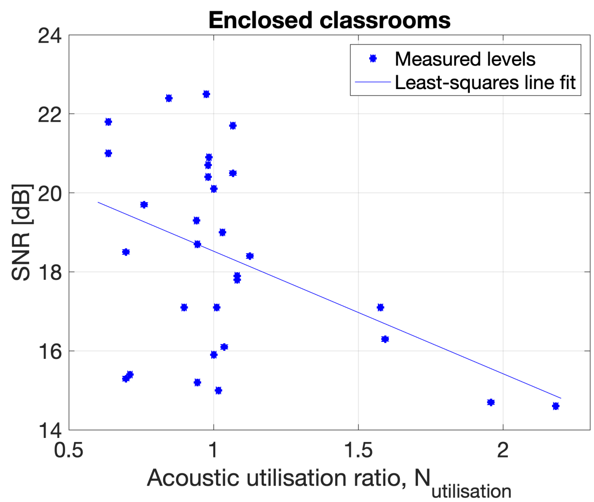

Figure 4.11: SNR with respect to acoustic utilisation ratio in enclosed classrooms (Plenary activity).

4.5 Average sound level, individual work

For individual work, the sample size is 31, including 18 sequences from enclosed classrooms and 13 from open-plan spaces. Figure 4.12 shows average sound pressure level, L_{Aeq}, for each school in the study.

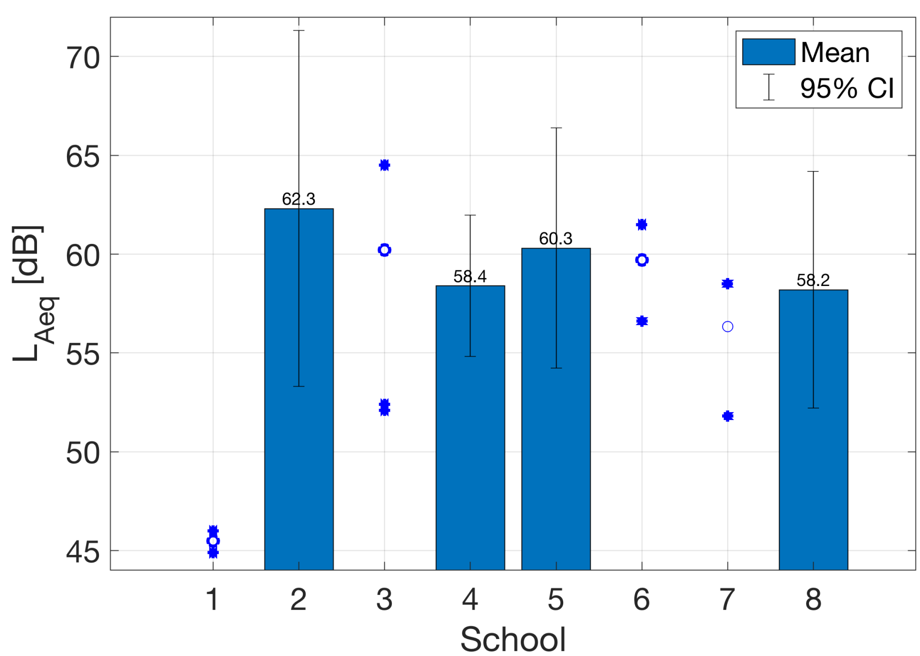

Figure 4.12: Individual work: L_{Aeq} with 95% confidence interval for each school in the study (School 1, 3, 6 and 7 are represented by individual data points (*) and a mean value (o) due to a sample size of 2 or 3).

Even though the selection of samples from some of the schools are small, an average level, $L_{Aeq,individual}$ across all schools can be found. This level is

$$L_{Aeq,individual} = 59.5 \pm 2.0 \text{ dB}, \qquad (n = 31) \tag{4.14}$$

L_{Aeq} is also found separately for enclosed classrooms and open-plan spaces.

$$L_{Aeq,individual,enclosed} = 58.7 \pm 2.7 \text{ dB}, \qquad (n = 18) \tag{4.15}$$

$$L_{Aeq,individual,open-plan} = 60.4 \pm 3.3 \text{ dB}, \qquad (n = 13) \tag{4.16}$$

4.5.1 Correlation with room dimensions

As shown in table 4.14, no room dimension correlates with the sound level during individual work. In enclosed classrooms, length ($r_s = 0.46$, $p_s = 0.05$) and maximum distance between teacher and a pupil ($r_s = 0.47$, $p_s = 0.05$) are close to being significantly correlated. This could be an indication that limiting the area where the pupils are spread reduces sound levels. Figure 4.13 shows the two dimension parameters that correlate with $L_{Aeq,individual,enclosed}$.

	Sample size	Width	Length	Height	Volume	Max dist.
$L_{Aeq,enclosed}$	n=18	$p_s = 0.49$	$p_s = 0.05$	$p_s = 0.11$	$p_s = 0.50$	$p_s = 0.05$
$L_{Aeq,open-plan}$	n=13	$p_s = 0.79$	$p_s = 0.66$	$p_s = 0.39$	$p_s = 0.49$	$p_s = 0.58$

Table 4.14: Statistical significance (p_s) of correlation between L_{Aeq} and room dimensions (Individual work).

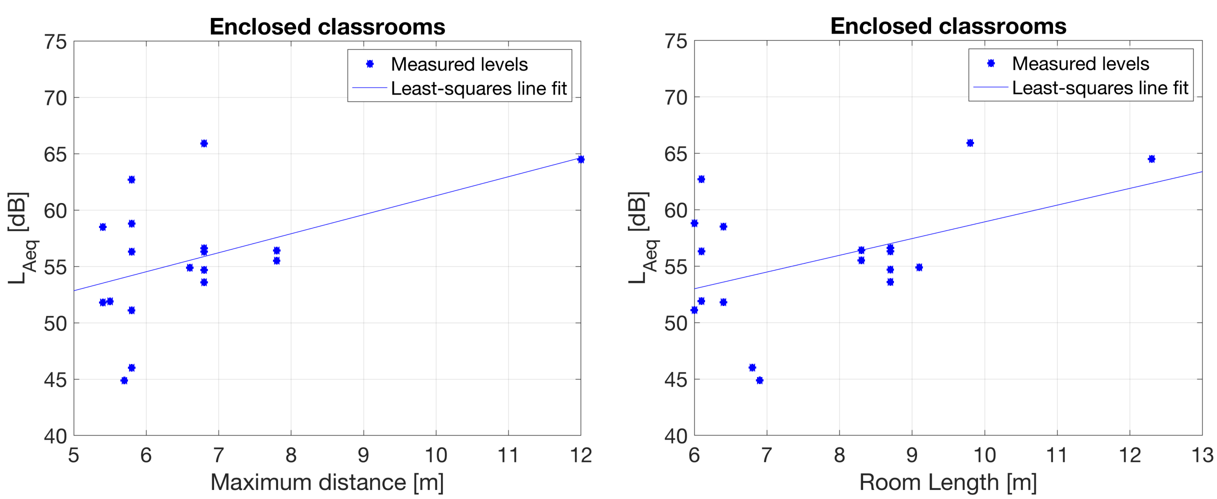

Figure 4.13: L_{Aeq} with respect to maximum teacher-pupil distance and room length in enclosed classrooms (Individual work).

4.5.2 Correlation with room acoustics and occupancy

As shown in table 4.15 and 4.16, no correlations are found between $L_{Aeq,individual}$ and room acoustics or room occupancy.

	Sample size	$\mathbf{T_{mf}}$	**Background noise**	**A**	**Hall radius**	$\mathbf{G_{mean}}$
$L_{Aeq,enclosed}$	n=18	$p_s = 0.87$	$p_s = 0.46$	$p_s = 0.47$	$p_s = 0.55$	$p_s = 0.47$
$L_{Aeq,open-plan}$	n=13	$p_s = 0.76$	$p_s = 0.44$	$p_s = 0.52$	$p_s = 0.53$	$p_s = 0.59$

Table 4.15: Statistical significance (p_s) of correlation betweeen L_{Aeq} and room acoustic parameters (Individual work).

	Sample size	**No.people**	**Acoustic utilisation ratio**
$L_{Aeq,enclosed}$	n=18	$p_s = 0.34$	$p_s = 0.87$
$L_{Aeq,open-plan}$	n=13	$p_s = 0.94$	$p_s = 0.50$

Table 4.16: Statistical significance (p_s) of correlation between L_{Aeq} and room occupancy (Individual work).

4.6 Average sound level, group work

For group work, the sample size is smaller than for plenary activities and individual work. School 4 and 6 had no group activities registered, and the total sample size was 15. The average sound pressure level, L_{Aeq}, for all group work sequences is

$$L_{Aeq,group} = 63.5 \pm 2.0 \text{ dB}, \quad (n = 15) \tag{4.17}$$

Again, the level is lower than the level found by Shield et al. in British schools, 67.7 dB ($\sigma = 5.5$). L_{Aeq} is also found separately for enclosed classrooms and open-plan spaces.

$$L_{Aeq,group,enclosed} = 64.1 \pm 2.5 \text{ dB}, \quad (n = 11) \tag{4.18}$$

$$L_{Aeq,group,open-plan} = 61.7 \pm 4.6 \text{ dB}, \quad (n = 4) \tag{4.19}$$

In contrast to individual work, the sound level is highest in enclosed classrooms during group work. However, the sample size is limited, especially for open-plan spaces (n=4).

4.6.1 Correlation with room dimensions and room acoustics

As shown in table 4.17 and 4.18, no correlations are found between $L_{Aeq,group}$ and room-dimensions or acoustics.

	Sample size	Width	Length	Height	Volume	Max dist.
$L_{Aeq,enclosed}$	n=11	$p_s = 0.70$	$p_s = 0.40$	$p_s = 0.54$	$p_s = 0.25$	$p_s = 0.40$
$L_{Aeq,open-plan}$	n=4	$p_s = 0.68$	$p_s = 0.68$	$p_s = 0.68$	$p_s = 0.68$	$p_s = 0.68$

Table 4.17: Statistical significance (p_s) of correlation between L_{Aeq} and room dimensions (Group work).

	Sample size	$\mathbf{T_{mf}}$	Background noise	A	Hall radius	$\mathbf{G_{mean}}$
$L_{Aeq,enclosed}$	n=11	$p_s = 0.65$	$p_s = 0.86$	$p_s = 0.35$	$p_s = 0.36$	$p_s = 0.47$
$L_{Aeq,open-plan}$	n=4	$p_s = 0.68$	$p_s = 0.52$	$p_s = 0.68$	$p_s = 0.68$	$p_s = 0.68$

Table 4.18: Statistical significance (p_s) of correlation between L_{Aeq} and room acoustics (Group work).

4.6.2 Correlation with room occupancy

	Sample size	No.people	Acoustic utilisation ratio
$L_{Aeq,enclosed}$	n=11	$p_s = 0.12$	$p_s = 0.79$
$L_{Aeq,open-plan}$	n=4	$p_s = 0.08$	$p_s = 0.27$

Table 4.19: Statistical significance (p_s) of correlation between L_{Aeq} and room occupancy (Group work).

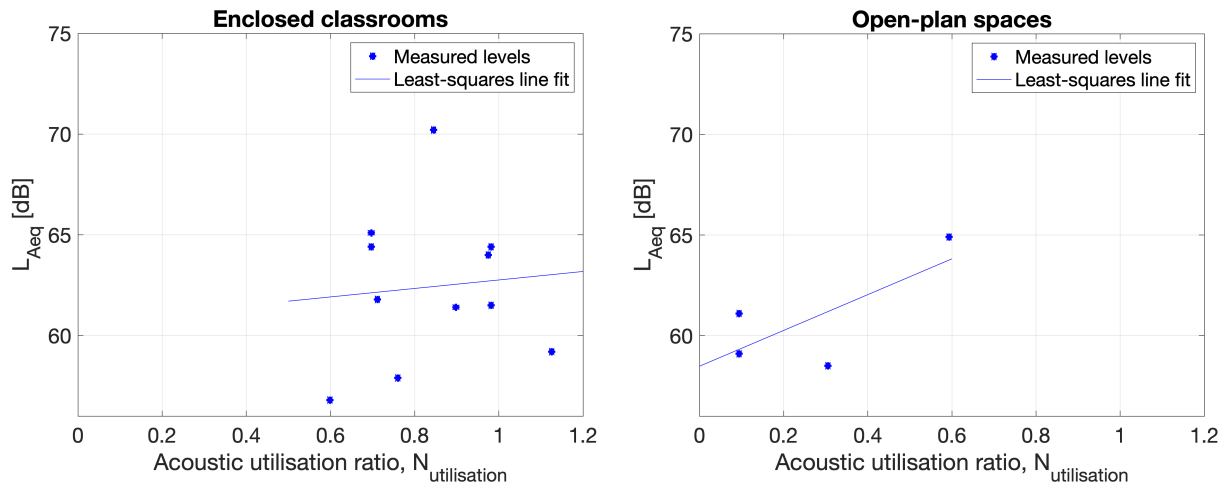

Figure 4.14: L_{Aeq} with respect to acoustic utilisation ratio in enclosed classrooms and open-plan spaces (Group work).

4.7 Average sound level, practical work and film

Practical work and film are small categories compared to the other three categories studied. As shown in figure 3.9, they occupy 5% and 4% of the time respectively. No analysis of correlation with room parameters will be made here due to the small sample size, but the average sound pressure level, L_{Aeq}, across all schools and room types are presented.

$$L_{Aeq,film} = 66.9 \pm 2.1 \text{ dB}, \qquad (n = 8) \tag{4.20}$$

$$L_{Aeq,practical} = 66.9 \pm 5.0 \text{ dB}, \qquad (n = 7) \tag{4.21}$$

5 Discussion

This study has investigated sound levels and correlations with room acoustic design. This chapter will begin with a section where limitations of the study are considered. Further, results from the study are discussed and summarised, and finally, further studies are suggested.

5.1 Limitations

Limitations are essential to consider when evaluating the results. Here, external disturbance from neighbouring classrooms and hallways are discussed, in addition to the study's sample size and use of room acoustic parameters intended for larger rooms.

5.1.1 External disturbance

As mentioned in section 3.5, some enclosed classrooms were poorly sound insulated from neighbouring rooms. It is likely that sound level measurements in these rooms were influenced by external activities. This could be the case in older buildings, but also in the newest buildings due to poorly insulated sliding doors used for flexible dividing of classrooms. In the two newest schools, the design of the sliding doors was poor. Either the locking mechanism did not work, or there was no locking mechanism on the door, increasing the sound leakage between rooms.

In lectures where a significant disturbance was perceived by the observer, a note was made in the observation sheet. It was therefore possible to identify these lectures in the analysis. Excluding sequences due to perceived external disturbance during the lectures is not an accurate method of sorting the data. Still, it can provide an indication of how this disturbance can affect the activity noise. At the same time, the sample size gets reduced and a larger uncertainty is associated with the results. Figure 5.1 shows activity noise with respect to room height in enclosed classrooms. The same plot was shown in figure 4.3, but here, the data points from lectures with a perceived external disturbance is indicated with a red 'o', whereas the other points are marked with a blue '*'. It is observed that a few of the disturbed lectures contributes to a steeper slope of the line fit. In particular the points at room height 2.6 m.

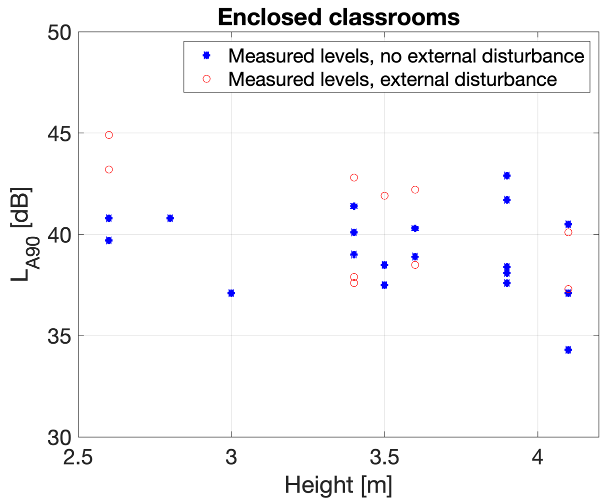

Figure 5.1: Activity noise, L_{A90} with respect to room height in enclosed classrooms (Plenary activity).

Ideally, one would consider the conditions in one single classroom without significant contributions from others, but it is realised that the measurements in this study does not fulfil that criteria. Results should be analysed and discussed accordingly, and it is emphasised that observed correlations are indications that can be further investigated in future studies.

5.1.2 Sample size

Generally, the study could benefit from a larger data set, including more schools and lectures. However, collecting the data is very time-consuming. It is therefore chosen to compare the results with studies from other countries to be able to do analysis with a larger perspective than data from this study can provide alone. Plenary activity is the activity with the largest sample size, and could therefore be considered the best documented variable from the study. Not as much data is collected for the individual work, and film, group- and practical work have very limited sample size as basis for the analysis.

5.1.3 Acoustic capacity and G_{mean}

Acoustic capacity and G_{mean} have been analysed for correlation with activity sound levels, but these parameters are not intended for rooms as small as typical classrooms. G_{mean} includes Barron's revised formula, which was developed due to effects observed in large concert halls [10]. For the acoustic capacity, Rindel mentions that the parameters for predicting acoustic conditions in restaurants may not apply to small rooms with a capacity of less than 30 persons [13]. Still, analysis of correlation between activity sound levels and G_{mean} and acoustic capacity, N, have been carried out. The occupancy relative to the acoustic capacity, named the acoustic utilisation ratio, has provided some interesting results, e.g. that significantly over-occupied rooms tends to have louder activity noise, and hence a lower signal-to-noise ratio than rooms with $N_{utilisation}$ below or around 1.

5.2 Educational activities

Figure 3.9 shows that plenary activities occupy 46% of the time spent on educational activities. As mentioned in section 1.1, a continuing development in learning methods is to be expected in schools. The traditional view of classroom activity is the plenary situation, something that is also reflected in the previous research on acoustic conditions in classrooms. However, in a white paper from the Norwegian government in 2008, the development of the teacher role is described as a move from being a mediator of knowledge to becoming a facilitator that supports the pupils in gaining knowledge. One could expect that this development would lead to a reduction in plenary activities. Here, no data is given on historical time distribution of activities, but the study shows that plenary activity occupies almost half of the time spent on educational activities. Plenary activity does not necessarily mean that the teacher is mediating knowledge. Also, the pupils are engaged in answering questions or discussing topics. Still, a room acoustic design that facilitate good speech intelligibility in a plenary activity is important. A recent trend in higher education is active-learning classrooms. These are rooms that facilitate co-operative work, and that are less focused on plenary activities. Based on the high amount of plenary activities in primary schools, active-learning classrooms might not be a good design goal here, due to its focus on group work, an activity that occupies only 12% of the time in primary schools, based on data from this study.

One could argue that a room design favours certain activities, and that the activities chosen by the teacher is predicted from the room they are using. As mentioned, the study includes both enclosed classrooms and open-plan spaces. Figure 3.10 shows the activity distribution sorted for room type. The biggest difference between the room types is the time spent on individual work. Open-plan spaces have 12% more individual work, and it seems that this activity replaces film and some of the plenary activity compared to the situation in enclosed classrooms. A possible explanation is that plenary- and film activities are considered loud, and that they are given less time to reduce disturbance between classes in the same area. However, plenary activities remain a large and important part of the lectures even though the room design varies. Group work seems to be occupying less time, regardless of room type. It could be that group work for extended periods of time is hard to conduct, due to the age of the pupils. The previous focus on the plenary situation in research on acoustic conditions therefore proves to be relevant for the situation in primary schools today. In addition, individual work seems to be an activity for which it is important to provide good acoustic conditions.

5.3 Activity noise, plenary activity

The average activity noise level, $L_{A90} = 41.3$ dB, ($\sigma = 3.0$), is low compared to previous studies in primary schools. A study in Finnish schools from 1991 by Pekkarinen and Viljanen reported L_{A90} from 40 dB to 59 dB [17], Shield et al. reported 49-57 dB in British schools in 2015 [5] and Oberdöster and Giesler reported L_{A95} from 52 dB to 61 dB in German schools in 2006 [18] [19]. These are levels across all activities, hence they are not directly comparable. However, the levels in this study are still lower than in the British and German studies, and in the lower range of the Finnish study.

Shield et al. also reported a separate activity noise level, $L_{A90} = 48.5$ dB, ($\sigma = 4.6$ dB), for plenary activities. The average activity noise level for plenary activities in British schools is therefore 7.2 dB higher than the level found from schools in Trondheim. Shield et al. do not specify whether the levels are corrected for background noise, but as shown in section 4.2, the impact of this correction is limited.

Separating enclosed classrooms and open-plan spaces, reveals that the enclosed rooms have lower activity noise levels ($L_{A90,enclosed} = 40.3$ dB, $L_{A90,open-plan} = 42.9$ dB), possibly explained by more disturbance from other lectures being conducted in the same area at the same time in open-plan spaces. The two newest schools in the study (2015 and 2018) have enclosed classrooms, as the majority of schools in Norway (estimate from 2011 shows that 11-12% are open-plan schools [20]). The results from enclosed classrooms can therefore be considered the most interesting for future classroom design projects.

5.3.1 Correlation with room acoustics

As shown in table 4.5 and figure 4.3, the activity noise level, L_{A90}, is significantly correlated with room height, based on the data from this study. There is an indication of the noise level being decreasing for increasing room height. In NS 8175:2012, many other room types have requirements for reverberation time as a function of height, but not classrooms. As mentioned in section 4.2.2, no correlation was found between L_{A90} and reverberation time, something that could have been expected based on findings from previous studies. Shield et al. measured higher mean values for reverberation time in enclosed classrooms (see table 4.4), and it is possible that activity noise has a stronger correlation with reverberation time for a selection of classrooms having higher reverberation times than those measured in this study. This could be due to a non-linear relationship between activity noise and reverberation time, a topic that was discussed in section 2.5.1.

The acoustic capacity is suggested by Rindel for predicting speech intelligibility in conversations in restaurants and cafes [13]. The parameter is therefore not intended to predict activity noise levels. Still, as shown in table 4.7, the room occupancy relative to the acoustic capacity provides a significant correlation with activity noise. In figure 4.5, it is observed that the level of activity noise has a wide spread and no clear trend for occupancies up to 10% over the acoustic capacity. Occupying the room more than this, seems to raise the activity noise level. Acoustic capacity is a function of room volume and reverberation time (equation 2.18), essentially a way of expressing absorption (equation 2.4). Yet, absorption and G_{mean} are not correlated to activity noise, as could be expected. Since room height is a variable independent of other variables, the relationship between activity noise and room height could be further investigated.

5.4 Speech level, plenary activity

As for the activity noise level, also the speech level found in this study, $L_{Aeq} = 59.0$ dB ($\sigma = 3.2$), is low compared to previous studies in primary schools. Pekkarinen and Viljanen reported L_{Aeq} from 58 dB to 79 dB in Finnish schools [17], Shield et al. reported 62 dB to 68 dB in British schools [5] and Oberdöster and Giesler reported 59 dB to 70 dB in German schools [18][19]. As mentioned in section 4.2, these are levels across all activities. Shield et al. also provides L_{Aeq} for the plenary activity separately, and it is found to be 63.3 dB. This is 4.3 dB higher than the level found from schools in Trondheim.

5.4.1 Correlation with room acoustics and noise

Interestingly, when analysing correlations with noise conditions, the speech level is significantly correlated to the activity noise, L_{A90}. Equation 4.9 and 4.10 provides the linear regression for speech level as a function of activity noise, and for enclosed classrooms, the slope is 0.6 dB/dB. This indicates that the Lombard effect is present in the classrooms during plenary activities.

Within the range of reverberation times in this study, the speech level is indicated to have a slope of 0.3 dB/0.1 s (but not significantly correlated) in the reverberation field (see figure 4.9). Considering equation 2.7, one would have a slope of 1 dB/0.1 s given a constant sound power level of the source. The slope of 0.3 dB/0.1 s could therefore be an indication of the teacher reducing the vocal effort for increasing reverberation time. When speaking in a plenary situation, one wants to have an impression of all the listeners in the room hearing the speech. Auditively, this impression is given to the teacher through reflections from room surfaces. Therefore, setting 0.4 s as superior conditions could be debated, especially given an indication of no significant correlation between activity noise and reverberation time. This topic has also been addressed in a study by Pelegrín-García et al. [6].

5.5 Signal-to-noise ratio, plenary activity

In a study on seventh- and eighth grade pupils in Canada, Bradley found that the speech intelligibility increased with increasing SNR up to 15 dB. Further increasing SNR did not improve the intelligibility [2]. Adults do not require the same level of SNR that young pupils do, emphasising the need for designing primary school classrooms with extra care. One should also include the perspective of universal design to provide good conditions for the hearing impaired, and SNR even better than 15 dB has been suggested in these rooms.

Given the speech level, and subtracting the activity- and background noise, the signal-to-noise ratio was found to be 19.0 dB for enclosed classrooms and 15.5 dB in open-plan spaces in this study. A significant level difference is observed between enclosed classrooms and open-plan spaces in this study. Both room types satisfy the 15 dB found by Bradley [2], but enclosed classrooms provide 3.5 dB better SNR-conditions. It should be noted that SNR is position dependent. The levels provided in this study are assumed to be valid for pupil positions beyond the hall radius of the room, but as shown in figure 2.3, the speech level increase for positions shorter from the sound source than the hall radius. Also, for the most distant positions, SNR can be lower if Barron's revised formula is taken into account. In open-plan spaces, the pupils were mostly gathered in a half-circle around the teacher during plenary activity, so the SNR could be better in their positions than what is indicated in the mean SNR here. Another good feature about the half-circle positioning, is that the teacher can lower the speech level, and the disturbance generated for other classes in the same area gets reduced.

5.5.1 Correlation with room acoustics and noise

In table 4.12 and figure 4.10 it is shown that the signal-to-noise ratio has a statistically significant correlation with background noise. Even though background noise was not significantly correlated to activity noise- or speech levels, it is interesting that a significant correlation with SNR is found. Also, it seems to improve for background noise levels below 28 dB, which is the requirement for maximum level in NS 8175:2012. All rooms with background noise below 30 dB satisfied the 15 dB recommendation by Bradley. However, for reverberation time there is a weaker correlation with SNR.

Also, the signal-to-noise ratio is significantly correlated to the occupancy with respect to the acoustic capacity in enclosed classrooms. The plot in figure 4.11 reveals that SNR has a wide spread and no clear trend for occupancies lower than or around the acoustic capacity of the room. Here, it looks as if other factors than the acoustic capacity determine the level. When the room is occupied above the acoustic capacity, the SNR gets clearly reduced. Interestingly, most rooms are occupied below the acoustic capacity, or up to 10% above.

5.6 Average sound level, other activities

The spread of the sound level in individual work is quite large between the schools, from 45.5 dB to 62.3 dB (shown in figure 4.12). School 1 stands out with low levels compared to the other schools. Unfortunately, the sample size is very small for school 1 (and also for three of the other schools), and it is realised that the result can be affected by this limited selection.

Individual work can be very silent during reading sequences, but gets louder when the pupils are solving exercises and might ask the teacher or fellow pupils for help during the work. With a small sample size, one risks to capture only one of these events, and that could have been the case in school 1. Possibly, reading could have been a separate category of activity since it normally does not include interaction between persons in the room.

The average sound pressure level in individual work, $L_{Aeq,individual} = 59.5$ dB, ($\sigma = 5.5$), is lower than the level found by Shield et al. in British schools, 62.3 dB ($\sigma = 7.1$). However, relevant to individual work, previous research on open-plan offices has shown that low intelligibility is more important than the level of the background noise when it comes to disturbing factors for concentrated work [21]. A low intelligibility needs to be balanced to the conditions required for the plenary activities. Possibly, this could be hard to achieve with the pupils positioned in the direct field of fellow pupils.

Group work is an activity where the acoustic capacity parameter from restaurant acoustics is relevant. The ideal is to have multiple conversations in the room at the same time, and that the internal signal-to-noise ratio on each group table is sufficient for speech intelligibility between the group members. Rindel's acoustic capacity is an established indicator for this purpose [13]. Table 4.19 shows that for enclosed classrooms, there is no correlation between the acoustic utilisation ratio and L_{Aeq} during group work. As earlier mentioned, most classrooms are occupied below or up to 10% above the acoustic capacity. As can be observed in figure 4.14, from the 11 samples of group sequences in enclosed classrooms, only one is occupied above the acoustic capacity. For open-plan spaces, none is occupied above the acoustic capacity. What can be realised through this result is that conditions for speech intelligibility in group conversations should be satisfactory, given that most classrooms are occupied below the acoustic capacity. Also, the total sound level in the room is not significantly correlated to the state of occupancy, as long as the room is not over-occupied relative to the acoustic capacity.

Practical work and film are not analysed for correlation with room acoustic conditions due to a low sample size. Possibly, further research on these activities is not required due to their limited part of the time distribution of educational activities.

5.7 Summary of statistically significant correlations

Before suggesting further studies on the topic of this thesis, a summary of the statistically significant correlations are given. These are all from plenary activities. No significant correlations were found between sound levels in other activities and room acoustic conditions. Table 5.1 summarises the correlations in enclosed classrooms.

Level	**Dependent variable**	$\mathbf{p_s}$	$\mathbf{r_s}$
L_{A90}	Height	0.02	-0.44
L_{A90}	Acoustic utilisation ratio	0.03	0.39
$L_{Aeq,plenary}$	L_{A90}	< 0.01	0.55
SNR	Background noise	0.01	-0.45
SNR	Acoustic utilisation ratio	0.01	-0.44

Table 5.1: Statistically significant correlations, enclosed classrooms

Table 5.2 summarises the correlations in open-plan spaces. Many of these correlations were not emphasised in the study, due to a positioning of the pupils in a half-circle around the teacher during plenary activities. Here, only a small part of the area was used, and many of the positions were in the direct field of the teacher.

Level	**Dependent variable**	$\mathbf{p_s}$	$\mathbf{r_s}$
L_{A90}	Width	0.03	-0.59
L_{A90}	Length	0.03	-0.57
L_{A90}	Maximum distance	0.03	-0.59
$L_{Aeq,plenary}$	Length	< 0.01	-0.75
$L_{Aeq,plenary}$	Volume	0.02	-0.61
$L_{Aeq,plenary}$	Maximum distance	< 0.01	-0.79
$L_{Aeq,plenary}$	T_{mf}	0.01	0.68
$L_{Aeq,plenary}$	L_{A90}	< 0.01	0.76
$L_{Aeq,plenary}$	A	0.01	-0.64
$L_{Aeq,plenary}$	Hall radius	0.01	-0.64
$L_{Aeq,plenary}$	G_{mean}	0.01	0.65
$L_{Aeq,plenary}$	Acoustic utilisation ratio	0.04	0.56

Table 5.2: Statistically significant correlations, open-plan spaces

5.8 Further studies

G_{mean} was only correlated to speech level in open-plan spaces, rooms that are approximately four times the size of enclosed classrooms on average. Considering the lack of significant correlation between activity noise and reverberation time, conditions for vocal effort in classrooms could be studied further. G could be included in such a study. In Pelegrín-García et al.'s study on vocal comfort for the teacher, short reverberation time was considered negative due to the increased vocal effort needed for intelligible speech [6]. With NS 8175:2012 considering reverberation time of 0.4 s as superior sound conditions, and this study showing no correlation between activity noise and a reverberation time with confidence interval between 0.47 and 0.61 s in enclosed classrooms, and between 0.40 and 0.62 s in open-plan spaces, it could be further studied if a longer reverberation time than 0.4 s would provide better conditions for plenary speech communication. Such a study could include investigations on how the teachers perceive vocal effort in various conditions.

Also, the indication of activity noise levels being significantly correlated to room height, but not to reverberation time, needs further investigation. The acoustic capacity is a function of volume and reverberation time, and since volume is a function of height, it is suspected that height also is contributing to the correlations found for occupancy with respect to acoustic capacity. Room height is not included in NS 8175:2012 for classrooms, but it is used in other room types. The findings in this study indicates that height could be an interesting parameter to consider also in classrooms. A possible solution could be to increase the maximum reverberation time and introduce a minimum height in order to reach satisfactory signal-to-noise ratio for speech communication.

Group work, practical work and film activities are limited in terms of the time distribution of educational activities. Future work could therefore be concentrated on the plenary activity and individual work in primary schools, based on data from this study.

6 Conclusion

Sound pressure levels in 40 lectures, conducted in 20 different classrooms in 8 primary schools in Trondheim, Norway, have been measured. The pupils were in 5th, 6th or 7th grade, with age between 10 and 13 years. The lectures were observed, and the sound levels categorised in five activities: plenary activity, individual work, group work, practical work and film. The average sound pressure level, L_{Aeq}, was collected for each activity in each lecture. Also, the activity noise levels, L_{A90}, defined as noise generated by the pupils during plenary activity was collected for each lecture. The activity sound levels were analysed in relation to room dimensions, acoustic conditions and occupancy in order to find correlations with room design.

L_{Aeq} and L_{A90} have previously been used by Shield et al. to represent speech and noise in plenary activities [5]. Hodgson et al. used a bimodal normal distribution curve fitting method for the same purpose [4], and these two methods have been compared. The comparison showed a significant correlation between the levels. Therefore, Shield et al.'s method has been used for analysis due to minimal requirements for post-processing.

Table 6.1 presents the average sound pressure levels, activity noise levels and signal-to-noise ratio found in primary schools in Trondheim.

	Plenary activity	**Individual work**	**Group work**	**Practical work**	**Film**
Enclosed classrooms	n=30	n=18	n=11	n=7	n=8
L_{Aeq} [dB]	59.4 ± 1.0	58.7 ± 2.7	64.1 ± 2.5	66.9 ± 5.0	66.9 ± 2.1
L_{A90} [dB]	40.3 ± 0.9				
SNR [dB]	19.0 ± 0.9				
Open-plan spaces	n=14	n=13	n=4		
L_{Aeq} [dB]	57.9 ± 2.1	60.4 ± 3.3	61.7 ± 4.6		
L_{A90} [dB]	42.9 ± 2.3				
SNR [dB]	15.5 ± 1.5				

Table 6.1: Average sound pressure levels across all schools, sorted for activity and room type. Practical work and film are across all room types, due to a low sample size.

The sound- and noise levels are lower than what similar studies conducted in Finland, England and Germany have found.

Previously, the plenary activity has been the main target in research on classroom acoustics. Data from this study indicates that the plenary activity remains a corner stone in the educational activities in primary schools, occupying 46% of the time spent on educational activities. Also, individual work is a large category, and together with plenary activity they account for 79% of the time spent on educational activities. From these results, one could argue that conditions for plenary and individual work are the most important activities to consider when designing classrooms in primary schools.

The average activity noise level, L_{A90}, found in plenary activities in this study could be used as a reference noise level in predictions of speech intelligibility through parameters like STI and U_{50}.

L_{A90} was found to have a statistically significant correlation ($p_s < 0.05$) with room height in enclosed classrooms. Also, occupancy with respect to the acoustic capacity, the latter a concept developed for conditions in restaurants and cafés, was significantly correlated to the activity noise level. However, no significant correlation was found with reverberation time or background noise, which are the parameters given in the building regulation NS 8175:2012. Since correlation with these parameters have been found in previous studies where reverberation times are longer, it could be assumed that the range in this latest study is too low to affect activity noise.

One statistically significant correlation was found with a parameter in NS8175. The signal-to-noise ratio in plenary activities was significantly correlated to background noise. Interestingly, background noise improved SNR also below 28 dB, which is the maximum level in the building regulation. Also, the occupancy relative to the acoustic capacity was significantly correlated to SNR.

In general, the data set in this study is limited in size, and has some limitations when it comes to disturbance from neighbouring classrooms. The results can therefore only provide indications for topics that need further studies. NS 8175:2012 defines a reverberation time of 0.4 s as superior conditions, but short reverberation times have been problematised due to negative effects on vocal comfort. With no correlations found between activity noise and reverberation time, it could be argued that the limits in the building regulation should be raised to a higher maximum value to increase vocal comfort for the teacher. One could also consider conducting further studies on room heights' effect on the activity sound level. This study have shown that the acoustic capacity correlates significantly with noise levels, but it is unclear why no correlation was found with absorption or G_{mean}, which are both functions of the same variables as the acoustic capacity, reverberation time and room volume.

Bibliography

[1] NS 8175:2012. Acoustic conditions in buildings - Sound classification of various types of buildings. Lysaker, NO: Standard Norge; 2012.

[2] Bradley JS. Speech intelligibility studies in classrooms. The Journal of the Acoustical Society of America. 1986 sep;80(3):846–854.

[3] Bradley JS. Optimising sound quality for classrooms. In: Brazilian Acoustical Association, editor. XX Meeting of SOBRAC. Rio de Janeiro, BR: SOBRAC; 2002. .

[4] Hodgson M, Rempel R, Kennedy S. Measurement and prediction of typical speech and background-noise levels in university classrooms during lectures. The Journal of the Acoustical Society of America. 1999 jan;105(1):226–233.

[5] Shield B, Conetta R, Dockrell J, Connolly D, Cox T, Mydlarz C. A survey of acoustic conditions and noise levels in secondary school classrooms in England. The Journal of the Acoustical Society of America. 2015 jan;137(1):177–188.

[6] Pelegrín-García D, Brunskog J, Rasmussen B. Speaker-Oriented Classroom Acoustics Design Guidelines in the Context of Current Regulations in European Countries. Acta Acustica united with Acustica. 2014 nov;100(6):1073–1089.

[7] Gracey & Associates. Acoustic glossary;. Accessed: 2019-04-22. Online. Available from: `http://www.acoustic-glossary.co.uk`.

[8] Kuttruff H. Room acoustics. 4th ed. London: Spon Press; 2000.

[9] NS-EN ISO 3382-2:2008. Acoustics. Measurement of room acoustic parameters. Part 2: Reverberation time in ordinary rooms. Lysaker, NO: Standard Norge; 2008.

[10] Barron M, Lee LJ. Energy relations in concert auditoriums. I. The Journal of the Acoustical Society of America. 1988 aug;84(2):618–628.

[11] Beranek L. The sound strength parameter G and its importance in evaluating and planning the acoustics of halls for music. The Journal of the Acoustical Society of America. 2011 may;129(5):3020–3026.

[12] Houtgast T, Steenken H. Past, present and future of the Speech Transmission Index. van Wijngaarden S, editor. Soesterberg, NL: TNO Human Factors; 2002.

[13] Rindel JH. Suggested acoustical requirements for restaurant, canteens and cafeterias. In: BNAM, editor. Baltic-Nordic Acoustics Meeting. Reykjavik, Iceland; 2018. .

[14] Løvås GG. Statistikk for universiteter og høgskoler. 2nd ed. Oslo: Universitetsforlaget; 2004.

[15] ISO 16032:2004. Acoustics - Measurement of sound pressure level from service equipment in buildings - Engineering method. Geneva, CH: International Organization for Standardization; 2004.

[16] Sato H, Bradley JS. Evaluation of acoustical conditions for speech communication in working elementary school classrooms. The Journal of the Acoustical Society of America. 2008 apr;123(4):2064–2077.

[17] Pekkarinen E, Viljancn V. Acoustic Conditions for Speech Communication in Classrooms. Scandinavian Audiology. 1991 jan;20(4):257–263.

[18] Oberdörster M, Tiesler G. Acoustic Ergonomics of School. F: Federal Institute of Occupational Safety and Health; 2006.

[19] Sala E, Rantala L. Acoustics and activity noise in school classrooms in Finland. Applied Acoustics. 2016 dec;114:252–259.

[20] Vinje E. Open-plan schools and important teacher competencies: What are teachers opinions? FORMakademisk. 2011 dec;4(2).

[21] Liebl A, Haller J, Jödicke B, Baumgartner H, Schlittmeier S, Hellbrück J. Combined effects of acoustic and visual distraction on cognitive performance and well-being. Applied Ergonomics. 2012 mar;43(2):424–434.

A Abbreviations and notation

Overline indicates mean value

Hat indicates regression value

SPL	Sound pressure level
AV	Audio/video equipment
SNR	Signal-to-noise ratio
NS	Norwegian Standard
ISO	International Organization for Standardization

p	Sound pressure
p_{ref}	Reference sound pressure, 20 μPa
L_p	Sound pressure level
L_W	Sound power level
L_{eq}	Equivalent continuous sound pressure level
L_A	A-weighted sound pressure level
L_n	Sound pressure level, statistical
ΔL	Level difference
K	Level correction

T	Reverberation time
T_{20}	Reverberation time, based on 20 dB decay
T_{mf}	Mid-frequency reverberation time, average of T at 500, 1000 and 2000 Hz
A	Absorption area
α	Absorption factor
S	Surface area
V	Room volume

c	Sound speed in air, 343 m/s
f_s	Schroeder frequency
r	Radius, distance from sound source
δ	$\frac{3\ln 10}{T}$, used in Barron's revised formula
r_h	Hall radius
DF	Directivity factor
G	Strength
G_{mean}	Mean strength across an interval between distance r_1 and r_2
STI	Speech transmission index
U_{50}	Useful-to-detrimental ratio
E_d	Direct sound energy
E_e	Early-arriving sound energy
E_l	Late-arriving sound energy
E_n	Background noise energy
$L_{N,A}$	Ambient noise level in a room with respect to occupancy
g	Average number of people per speaking person
N	Total number of people in the room
N_s	Group size
N_{max}	Acoustic capacity
$N_{utilisation}$	Occupancy with respect to acoustic capacity
A_p	Absorption area per person
$\mu 1$	First mean value of bi-modal normal distribution fitting
$\mu 2$	Second mean value of bi-modal normal distribution fitting
r_s	Correlation
p_s	Statistical significance
n	Sample size
σ	Standard deviation
$\hat{\alpha}$	Regression coefficient
$\hat{\beta}$	Regression coefficient

B Equipment list, measurements in schools

- Norsonic Nor140 - Precision sound analyser.
  - Serial number: 140392.
  - Calibrated by Norwegian accreditation 2019-01-10.
- Norsonic Norsonic Type 1209/13389 microphone.
- Norsonic 1251 calibrator, 114 dB 1000 Hz.
- Manfrotto stand
- Paper bags
- Leica distance meter

C Equipment list, pilot reverberation time measurement

- EASERA - Universal measuring platform v. 1.2.13, software on Windows computer
- Roland - Studio Capture 16x10, audio interface
- Rotel RB-1552 MKII Power amplifier.
- Omnidirectional loudspeaker, custom built at NTNU.
- Bruel & Kjær 4190 Free-field 1/2" microphone
- Norsonic Front end type 336 microphone pre-amplifier
  - Serial number: 18508.
- Norsonic Nor140 - Precision sound analyser.
  - Serial number: 140392.
  - Calibrated by Norwegian accreditation 2019-01-10.
- Norsonic Norsonic Type 1209/13389 microphone.
- Norsonic 1251 calibrator, 114 dB 1000 Hz.
- Paper bags
- Leica distance meter
- All necessary cables and stands

D Matlab script: main.m

```
clear
close all

%% main.m created by Erlend Bolstad 2019
% The script takes a folder of excel-files as input. The files contain
% observations from lectures and measurement data from a sound analyser.
% Observations, room dimensions, room actoustics and levels are collected
% in a large matrix with each row represetning one activity type in one
% lecture.

%% Define file destination
source_dir = '/Users/erlendbolstad/OneDrive - NTNU/Master/alldata/';

%% Create list of filenames
source_files = dir(fullfile(source_dir, '*.xlsx'));

%% Create checklist activities
activity = {'Plenary','Plenary_p','Group','Group_p','Individual',...
    'Individual_p','Practical',...
    'Practical_p','Film','Film_p','notused'};
% _p means projector was on during the activity

%% For-loop for importing data from .xlsx-files.
count = 1; % Row number

for i = 1:length(source_files)
    for j = 1:11    % 1=Plenary 2=Plenary_p 3=Group 4=Group_p...
                    % 5=Individual 6=Individual_p
                    % 7=Practical 8=Practical_p 9=Film 10=Film_p 11=notused
          data = xlsread(fullfile(source_dir, source_files(i).name),j+2);

          if isempty(data) == 1
              continue
          else
          levels = data(:,[11 27]); % 11=L_{Aeq}, 27=L_{Aeq},
                                    % corrected for background noise

              % Register activity code: 1=Plenary 2=Group 3=Individual
              % 4=Practical 5=Film 99=notused
              if j==1 || j==2
                Bigg2(count,1) = 1;
              elseif j==3 || j==4
                Bigg2(count,1) = 2;
              elseif j==5 || j==6
                Bigg2(count,1) = 3;
              elseif j==7 || j==8
                Bigg2(count,1) = 4;
```

```
            elseif j==9 || j==10
              Bigg2(count,1) = 5;
            elseif j==11
                Bigg2(count,1) = 99;
            else
            end

    %% Get basic data (Volume, roomnumber, subject etc.)
    [num, ¬, raw] = xlsread(fullfile(source_dir, source_files(i).name),1);
    [Bigg2(count,2:15),txtdata{count}] = getbasic(num,raw);
    clearvars num raw

    %% Activity noise L_Aeq Hodgson method and L_Aeq/L_A90 Shield-method
    if j==1 || j==3 || j==5 || j==7 || j==9
        Bigg2(count,16) = 0;  % no AV used
    else
        Bigg2(count,16) = 1;  % AV used
    end

    if Bigg2(count,1)==1 || Bigg2(count,1)==5  % Plenary and film use
                                               % bimodal normal distribution
                                               % fit
        %Bigg2(count,17:22) = hodgson2plot(levels(:,2),count); % with plot
        Bigg2(count,17:22) = hodgson2(levels(:,2)); %no plot
        else
            %Bigg2(count,17:22) = hodgson1(levels);
            Bigg2(count,17:22) = hodgson1plot(levels(:,2)); % Normal
                                                            % distribution
                                                            % with one
                                                            % curve
        end
        Bigg2(count,[23 25]) = shield(levels(:,1)); % L_{Aeq}/L_{A90}
        Bigg2(count,[24 26]) = shield(levels(:,2)); % L_{Aeq}/L_{A90},
                                                    % corrected for
                                                    % background noise

    %% LA90 frequency, octave bands
    Lfeq=round(data(:,1:11),1);
    Lfeq(:,12:22)=round(data(:,17:27),1);
    Lfeq_sort=sortrows(Lfeq,22);
    Lfeq_eq=round(10*log10(sum(10.^(Lfeq/10))/length(Lfeq)),1);

    Lfeq_90=Lfeq_sort(round(length(Lfeq_sort)*0.1),:);
    for k=1:11
        Bigg2(count,k+32)=[Lfeq_eq(k)];
        Bigg2(count,k+43)=[Lfeq_eq(k+11)];
        Bigg2(count,k+54)=[Lfeq_90(k)];
        Bigg2(count,k+65)=[Lfeq_90(k+11)];
    end


    %% T_mf
    rt = xlsread(fullfile(source_dir, source_files(i).name),14);
    Bigg2(count,27) = rev(rt);
    clearvars rt

    %% Background noise
    noise_data = xlsread(fullfile(source_dir, source_files(i).name),15);
    [Bigg2(count,28),Bigg2(count,29)] = bn(noise_data);
    noise_data_p = xlsread(fullfile(source_dir, source_files(i).name),16);
    [Bigg2(count,30),Bigg2(count,31)] = bn(noise_data_p);
    Bigg2(count,32) = Bigg2(count,28)-Bigg2(count,29);

```

```
    if Bigg2(count,16)==0
        for m=1:3
        noise_freq(m,:)=[10*log10(sum(10.^(0.1*noise_data(m,17:19)))),...
                         10*log10(sum(10.^(0.1*noise_data(m,20:22)))),...
                         10*log10(sum(10.^(0.1*noise_data(m,23:25)))),...
                         10*log10(sum(10.^(0.1*noise_data(m,26:28)))),...
                         10*log10(sum(10.^(0.1*noise_data(m,29:31)))),...
                         10*log10(sum(10.^(0.1*noise_data(m,32:34)))),...
                         10*log10(sum(10.^(0.1*noise_data(m,35:37)))),...
                         10*log10(sum(10.^(0.1*noise_data(m,38:40)))),...
                         10*log10(sum(10.^(0.1*noise_data(m,41:43)))),...
                         10*log10(sum(10.^(0.1*noise_data(m,44:46))))];
        end
        for l=1:10
            Bigg2(count,l+76)=bnfreq(noise_freq(:,l));
        end
    elseif Bigg2(count,16)==1
        for m=1:3
        noise_freq(m,:)=[10*log10(sum(10.^(0.1*noise_data_p(m,17:19)))),...
                         10*log10(sum(10.^(0.1*noise_data_p(m,20:22)))),...
                         10*log10(sum(10.^(0.1*noise_data_p(m,23:25)))),...
                         10*log10(sum(10.^(0.1*noise_data_p(m,26:28)))),...
                         10*log10(sum(10.^(0.1*noise_data_p(m,29:31)))),...
                         10*log10(sum(10.^(0.1*noise_data_p(m,32:34)))),...
                         10*log10(sum(10.^(0.1*noise_data_p(m,35:37)))),...
                         10*log10(sum(10.^(0.1*noise_data_p(m,38:40)))),...
                         10*log10(sum(10.^(0.1*noise_data_p(m,41:43)))),...
                         10*log10(sum(10.^(0.1*noise_data_p(m,44:46))))];
        end
        for l=1:10
            Bigg2(count,l+76)=bnfreq(noise_freq(:,l));
        end
    end
    clearvars noise_data noise_data_p m l

    % Hall radius
    c=343;
    DF=2;
    Bigg2(count,87)=sqrt((24*log(10)*Bigg2(count,13)*DF)/...
                    (16*pi*c*Bigg2(count,27))); % Directivity factor set to
                                                % 2. sound speed, C, set to
                                                % 343

    % G_mean
    r1=1.5; %closest position pupil, 1,5 m
    Δ=(3*log(10))/Bigg2(count,27);
    G_trad=(31200*Bigg2(count,27))/(DF*Bigg2(count,13));
    G_m=10*log10(G_trad*(1/(Bigg2(count,15)-r1))*(c/(2*Δ))*...
        (exp(-(2*Δ*r1)/c)-exp(-(2*Δ*Bigg2(count,15))/c)));
    Bigg2(count,88)=G_m;

    % A
    Bigg2(count,89)=0.163*(Bigg2(count,13)/Bigg2(count,27));

    % N_max
    Bigg2(count,90)=Bigg2(count,13)/(20*Bigg2(count,27));

    % N_ratio,
    Bigg2(count,91)=(Bigg2(count,8)+Bigg2(count,9))/Bigg2(count,90);

    %% New row
    count = count+1;

```

```
        end
        end
    end
    clearvars i j


    Big2 = array2table(Bigg2,'VariableNames',{'Activity','School',...
            'SchoolType','Room','RoomType','Grade','Subject','Pupils',...
            'Adults','RoomWidth','RoomLength','RoomHeight','RoomVolume',...
            'MicDistance','MaxDist','ProjectorOn','Duration','mu1','sigma1',...
            'mu2','sigma2','normfact','LAeq','LAeq_corr','LA90','LA90_corr',...
            'Tmf','Bn','Bn_A50','Bn_p','Bn_p_A50','Diff','feq_315','feq_63',...
            'feq_125','feq_250','feq_500','feq_1000','feq_2000','feq_4000',...
            'feq_8000','feq_16000','feq_all','feq_315_c','feq_63_c',...
            'feq_125_c','feq_250_c','feq_500_c','feq_1000_c','feq_2000_c',...
            'feq_4000_c','feq_8000_c','feq_16000_c','feq_all_c','f90_315',...
            'f90_63','f90_125','f90_250','f90_500','f90_1000','f90_2000',...
            'f90_4000','f90_8000','f90_16000','f90_all','f90_315_c',...
            'f90_63_c','f90_125_c','f90_250_c','f90_500_c','f90_1000_c',...
            'f90_2000_c','f90_4000_c','f90_8000_c','f90_16000_c','f90_all_c',...
            'f315_bn','f63_bn','f125_bn','f250_bn','f500_bn','f1000_bn',...
            'f2000_bn','f4000_bn','f8000_bn','f16000_bn','r_h','G_mean','A',...
            'N_max','N_ratio'});
```

E Matlab function: hodgson2.m

```
function [Bigg] = hodgson2(LAtable)

%% hodgson2.m created by Erlend Bolstad 2019
% Function that takes a table of levels as input.
% A bimodal normal distribution fit is applied to a histogram of levels.
% The output of the function includes duration of the sequence and
% two peak levels and their variance. Finally a normfactor describing
% the deviance between peaks is included in the output

%% Create table
LAeqtable = table;

%% Allocate imported array to column variable names
LAeqtable = LAtable;

pdf_normmixture = @(LAeqtable,p,mu1,mu2,sigma1,sigma2) ...
                         p*normpdf(LAeqtable,mu1,sigma1) + ...
                             (1-p)*normpdf(LAeqtable,mu2,sigma2);

pStart = .5;
muStart = quantile(LAeqtable,[.25 .75]);
sigmaStart = sqrt(var(LAeqtable) - .25*diff(muStart).^2);
start = [pStart muStart sigmaStart sigmaStart];

lb = [0 -Inf -Inf 0 0];
ub = [1 Inf Inf Inf Inf];
paramEsts = mle(LAeqtable, 'pdf',pdf_normmixture, 'start',start, ...
                          'lower',lb, 'upper',ub);

statset('mlecustom');

options = statset('MaxIter',300, 'MaxFunEvals',600);
paramEsts = mle(LAeqtable, 'pdf',pdf_normmixture, 'start',start, ...
                          'lower',lb, 'upper',ub, 'options',options);

s=length(LAeqtable)*0.2;

Bigg(:,2) = round(paramEsts(2),1);
Bigg(:,4) = round(paramEsts(3),1);
Bigg(:,3) = round(paramEsts(4),1);
Bigg(:,5) = round(paramEsts(5),1);
Bigg(:,1) = s;
Bigg(:,6) = (paramEsts(3)-paramEsts(2))/mean(paramEsts(4:5));
end
```

F Matlab function: shield.m

```
function [Bigg] = shield(LAeqtable)

%% shield.m created by Erlend Bolstad 2019
% Function that takes a table of levels as input.
% Calculates the logarithmic mean, L_{Aeq}
% Sorts the table and finds the level that is exceeded 90% of the time.

Bigg(:,1)=round(10*log10(sum(10.^(LAeqtable/10))/length(LAeqtable)),1);
Lsort=sort(LAeqtable);
Bigg(:,2)=Lsort(round(length(Lsort)*0.1));

end
```

NTNU
Norwegian University of
Science and Technology